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DISCOVERY OF THE DISK OF ONYCHOCRINUS, AND FURTHER REMARKS ON THE CRINOIDEA FLEXIBILIA

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The Disk of Onychocrinus

In the year 1888 Wachsmuth and Springer[1] published their "Discovery of the Ventral Structure of *Taxocrinus*," based upon a remarkable specimen of *T. intermedius* from the Kinderhook group of the Subcarboniferous, at Le Grand, Iowa. Until that time nothing whatever had been known concerning the structure of the tegmen in the Crinoidea Flexibilia; but numerous theories about it had been discussed, all of them based upon the assumption that it was in the nature of a closed vault analogous to that of the Camerata, and supposed to be common to all the paleozoic Crinoids. The specimen above mentioned, however, demonstrated that in *Taxocrinus*, and presumably in the Flexibilia generally, the tegmen had an open mouth, surrounded by five oral plates, with ambulacra passing in between them, after the manner of the Recent Crinoids. This interpretation has been accepted by all subsequent writers, and our figure of the tegmen of *Taxocrinus* has been copied in almost every treatise on Crinoids or general paleontology published since that time.

In that paper it was stated that traces of alternating ambulacral plates had been seen in a specimen of *Onychocrinus*, but not the orals,

[1] *Proceedings*, Academy of Natural Science, Philadelphia, November, 1888, p. 337.

nor any part of the perisome. Messrs. Lyon and Casseday, in their description of *Onychocrinus exsculptus*,[1] gave a partial description of the vault, which they thought to be similar to that of the Asteroidea. They observed, extending toward the arms, "five rays composed of two rows of large, granulose pieces, one row alternating with the other," and in the fields bordered by these five rays some interstitial pieces which were "very small, granulose, and arranged without any apparent order." They were unable, from the fragmentary condition of their specimens, to obtain any information as to the central portion.

As the genus *Onychocrinus* represents the most specialized form of the group—one of the latest developed and latest surviving—it has seemed a matter of special interest to ascertain the exact structure of its ventral side. Its calyx exhibits, in a striking degree, the two characteristics of the group—massiveness and flexibility. Except at the very base, where they are rather thin, the plates are thick and heavy, and are closely laid together, like bricks in a pavement. The interbrachial system connecting the rays dorsally is composed of strong and thick plates, while the brachials are of great depth, and have a very shallow ambulacral groove. Nevertheless, the plates of this powerfully built calyx must have possessed an immense amount of mobility among themselves, for we find it preserved in a great variety of positions. In some specimens the rays are folded together, and in others they are spread out horizontally. These changes of position, while they involve all the brachial and interbrachial plates, did not cause any marked opening or gaping of the sutures; but in some singularly perfect manner the plates seem to have been capable of sliding upon each other by their apposed surfaces, and thus accommodating themselves to any degree of flexure.

The tegmen of such a calyx must necessarily have been of an extremely pliant nature. But all attempts to obtain it, in sufficiently perfect condition to disclose the nature of the mouth and oral structures generally, have hitherto proved futile. At Crawfordsville, Ind., where two species have been found in large numbers, the specimens almost always have the rays so closely folded together that the tegmen cannot be got at, and, besides, the preservation of fine details

[1] *American Journal of Science*, (2), Vol. XXIX, p. 79.

at that locality is poor. At Burlington specimens of this genus have not been found in a matrix soft enough to permit the exposure of such delicate structures. At Le Grand, where the *Taxocrinus* disk was found, *Onychocrinus* does not occur—not having been developed in America, so far as yet known, earlier than the Upper Burlington Limestone.

The only known material which seemed to offer a possibility of discovering the tegmen of this genus was that from Indian Creek, Montgomery County, Ind., where *Onychocrinus ulrichi* was obtained in considerable numbers; many of them with the rays completely spread out horizontally, and imbedded in a fine-grained, homogeneous matrix, admitting of minute cleaning. In collecting, these were usually found with the dorsal side exposed and the ventral side embedded, and when the collection was first made from that locality, several such specimens were cleaned without yielding the desired result. Remnants of the disk were observed in some, broken and lying in confusion in the bottom of the cavity, and showing but little of the structure. It was clear that the disk was of such extreme flexibility that it had been forced by the pressure of the calcareous matrix down into the dorsal cavity, and was generally broken and displaced. Recently I undertook the search afresh, and by very delicate manipulation had over a dozen of the best specimens with outspread rays completely freed from the matrix on the ventral side—a very tedious and laborious operation, and sometimes sadly destructive of fine specimens. Some were dissected by the removal of the calyx plates, in hope of gaining access to the under side of the disk.

These efforts were finally rewarded by uncovering, in several specimens, the tegmen in such position as to give a complete elucidation of the structure. The exceptional condition of the specimens, and the exceedingly fine and homogeneous character of the material in which they were imbedded, were all that rendered the discovery of these details possible. With the light afforded by them several others in which the structures were only partially preserved—though much displaced—became easily understood. The construction of this disk is upon the same general plan as that of *Taxocrinus*, but exhibits a very interesting modification of it. It is gratifying to find, in this new discovery upon an additional genus, a full confirmation

of our former interpretation of the tegmen of the whole Flexibilia group.

The two most instructive specimens are figured herewith (Plate IV, Figs. 1 and 2), and another which gives a good general idea of the disk (Plate IV, Fig. 3). Fig. 1 will be readily understood by the simple statement that it is the ventral surface of the disk. In Fig. 2 we see the inner floor, or under side of the same structure, which has been exposed by removing the basal, radial, brachial, and interbrachial plates. The disk is so pliant and frail that it is invariably found more or less sunken down, and lying on the bottom of the dorsal cavity. This is why it appears concave in Fig. 1, and convex in Fig. 2. The greater portion of the disk was clearly membranous, with calcareous spicules and granules imbedded in it; except in the oral center, and in the ambulacral regions, which are occupied by rows of large elongate, alternating plates, more or less tumid exteriorly, and keeled on the under surface. These converge in the middle into a rounded, open mouth, which is surrounded by a pyramid of four small, triangular oral plates, meeting a fifth large one on the posterior side. This posterior oral is the most remarkable feature of the disk. It is of enormous size relatively to the other structures, and is very thick and heavy. It is preserved in nearly all the specimens in which the ventral side was cleaned, but as it was usually found lying detached in the bottom of the dorsal cavity, its identity was not recognized until after I found it in place in this specimen (Fig. 1). It is spade-shaped, and the end toward the oral aperture is somewhat hollowed to form one side of the mouth. Both the exterior and interior surfaces of this large plate are shown in the figures—the latter view being at the upper part of Fig. 2. In Fig. 1 this plate seems to be divided by a transverse suture, but I do not find this to be so in other specimens.

The four smaller oral plates are delicate, and they seem to vary somewhat in shape in the different specimens—sometimes appearing quite slender and elongate, and irregular in size. Much of this irregularity, however, may be due to the accidents of fossilization, producing such compression and displacement as might greatly modify the shape and proportions of these delicate structures. In the specimen represented by Fig. 1, two of these plates are perfect and undisturbed, the third somewhat flattened laterally, and the

fourth is pushed partly under the others, so that not much of it can be seen in this view. They are triangular, and fit closely together at the sides, forming a small pyramid. As they lie in the bottom of the calyx they seem to stand somewhat erect, but in their natural position, with the disk normally distended, it is probable that they would appear more flattened, like the orals in the recent genus *Holopus* (Plate V, Fig. 8). They were perhaps also movable, capable of opening and closing at the will of the animal. These small orals are not always so regular as this. Fig. 4, Plate IV, which is an enlarged view of the central part of the disk in another specimen, shows the irregular, elongate, toothlike appearance which they sometimes present. The rounded object at the right of the three linear plates is evidently a foreign body, but the other four suggest a stage of almost complete resorption.

The ambulacra are composed of relatively heavy, elongate plates. They meet by close sutures, and are convex on the outer surface. The inner surface is marked by keel-like elevations, which may have served as lines for muscular attachment. They extend from the oral center along the rays to the point of bifurcation, beyond which they have not been traced; but they no doubt follow the arms in a modified form. The three anterior ambulacra pass in between the bases of the four small orals in a similar manner as they do between the plates of the oral pyramid in *Holopus*. The two posterior ambulacra first meet the outer corners of the large oral—at which points there are some larger plates, apparently serving as braces, or supports, for the tegmen—thence they run along the edges of the posterior oral, which sometimes appears to be grooved, and pass in toward the mouth at the junction between it and the smaller orals. Whether these strong alternating plates were covering pieces arching over the food-grooves, or were merely some kind of subambulacral plates forming a support for more delicate plates which were not preserved, or for an ambulacral structure composed only of soft parts, I am unable to determine. The variation in size and shape of ambulacrals in the living Crinoids is very great, and there is no reason why plates as large as these may not have served as covering pieces, opening out when the orals did to admit the inward passage of the food-bearing currents.

The connecting integument between the ambulacra was mem-

branous, reinforced by a close growth of calcareous particles similar to what has been observed in *Taxocrinus*, *Uintacrinus*, and the disk of many Recent Crinoids. It extends far out along the rays, bordering the ambulacra as far as they have been traced. It is extremely frail in the fossil, and is of a slightly darker color than the calyx plates.

In this species the anal plates are very prominent, rising from the posterior basal in the form of a finger-like series, which makes a reverse curve toward the ventral side, the distal end going to the right. It is finely preserved in several of the specimens, but does not appear so plainly in Fig. 1, Plate IV, where it has fallen under the posterior edge of the large oral; but in Fig. 3 it is perfectly shown. It is composed of strong and solid plates, well rounded dorsally, and connecting at the inner side with the membranous integument of the disk, which is sometimes found folded longitudinally alongside of it. This anal appendage does not seem to be actually a tube, as I cannot detect any longitudinal opening or canal through it. In one specimen I find it standing apart from the other plates, and the inner side entirely enveloped in the membrane—thus indicating that the row of strong plates more probably served as a support for a soft tube or opening formed by the protuberance of the membrane itself.

The exact position of the anal opening has not been observed, but it was no doubt at or near the end of the anal series. So far as I can see, the distal end becomes merged in the perisome of the disk, and it is probable that the aperture for the hind gut was at that point. In all the specimens the structures are broken down and displaced in this part, being involved in the downfall of the large posterior oral, so that the exact fact cannot be ascertained. I have no doubt that the anal structure was substantially the same as in *Taxocrinus intermedius*, in which, however, the anal opening has not been definitely located.

In considering the significance of the disk of *Onychocrinus* as disclosed by these discoveries, we must refer to the observed course of development of the larva in one of the living representatives of the Flexibilia, *Antedon rosaceus*. Of this I take the following abstract from Dr. W. B. Carpenter's account[1] of this species in its Penta-

[1] *Philosophical Transactions*, 1866, p. 727.

crinoid stage, between the time of emergence from the embryo and that of casting off the stem, reference being had to the figures herein:

The animal consists in the first instance of the stem and calyx alone, not even rudiments of arms being distinguishable. The calyx completely incloses the visceral mass, its oral valves when drawn together meeting over the mouth, and when these open out it takes the form of an inverted bell. Its oral part is composed of five oral plates, the approximation of which forms a five-sided pyramid with its truncated apex pointing upwards—though they are usually erected as separate valves, to allow the oral apparatus to be projected from within them. The mouth of the bell, when the oral valves are expanded, is entirely occupied by the oral tentacular apparatus. The general aspect of the young Pentacrinoid, as seen with the tentacular apparatus retracted in a spirit specimen, is shown in Plate V, Fig. 1. The oral plates are triangular in form, their apices pointing upward, but capable of closing so as to form a five-sided pyramidal cover to the calyx (Plate V, Fig. 3). With the further development of the Pentacrinoid, a remarkable change takes place in the relative position of these orals. They do not increase with the other elements of the growing calyx. They continue to embrace the circle of oral tentacles, the diameter of which comes to bear a smaller and yet smaller proportion to that of the ventral surface of the disk; and thus it comes to pass that the circlet of oral plates detaches itself from the summits of the radials on which it was previously superimposed, and is *relatively* carried inward by the great enlargement of the circle formed by the latter—the space between the two series being now filled in only by the membranous perisome, which is traversed by the five radial canals (ambulacra) that pass out from the oral ring between the oral valves to the bifurcation of the arms (Plate V, Fig. 7).

Before the body of the Pentacrinoid drops off its stem, an incipient resorption of the oral plates is discernible, commencing along the margins of the apical portion, so that these plates lose their triangular form and become somewhat spear-shaped (Plate V, Fig. 7). This absorption continues in various degrees; sometimes the upper half of the oral plate disappears, and in other cases the marginal portions only of the upper part of the plate have been removed,

leaving a sort of central tongue projecting upward; finally, soon after the Crinoid becomes free, they completely disappear.

The condition presented by the disk of *Onychocrinus* may be considered to be somewhat approximate to that of the last stage of the *Antedon* Pentacrinoid before it casts off the stem, and before the orals are finally resorbed (Plate V, Fig. 7). In the irregularity in the size and shape of the orals in these fossils we may perhaps recognize some of the different stages of absorption in the *Antedon* larva as above described.

We may also compare the morphological condition of our disk with that of P. H. Carpenter's remarkable recent genus *Thaumatocrinus*.[1] His solitary specimen, of which I reproduce one of his figures (Plate IV, Fig. 6), was very small, probably in a young stage. If we imagine it in a more mature condition, with the orals pushed inward and made relatively smaller by the growth of perisome, and the anal tube more or less enveloped by it, we shall have a disk somewhat analogous to ours. Of course the enormous posterior oral of the *Onychocrinus* disk does not find a parallel in any of the recent tegmens. Its pronounced bilateral symmetry is a paleozoic characteristic, strongly marked among the Camerata and Inadunata, as well as in many of the Flexibilia. It is possible that the posterior oral is a madreporite, as has been found in many Cyathocrinidæ. It seems to be perforated with somewhat scattered pores in several specimens, one of which I figure, twice enlarged (Plate IV, Fig. 4). This may be something like the water-pores in the orals of *Holopus*, as shown in Carpenter's figure above cited (Plate V, Fig. 8).

Since obtaining the above-mentioned specimens, I have succeeded in exposing the disk of a specimen of *Onychocrinus exsculptus*, from Crawfordsville—a thoroughly distinct species. While by no means so perfect, it shows that the structure is substantially the same. I have also obtained another disk of *Taxocrinus*, from a much later horizon than *T. intermedius*, which exhibits the same characteristics as the latter species.

Further Remarks on the Crinoidea Flexibilia

In a paper in the *American Geologist* for August, 1902 (pp. 88 ff.), I offered some suggestions looking to the systematic arrangement of

[1] *Philosophical Transactions*, Royal Society, Part III (1883), p. 919.

the Impinnata division of the Crinoidea Flexibilia, dividing them into two main family groups—Ichthyocrinidae and Taxocrinidae. Some of Angelin's Silurian genera, as stated at that time, were arranged with doubt. Since then I have received from Mr. G. Liljevall, of the National Museum at Stockholm—who has at my request made a careful examination of the Swedish material belonging to this group—a set of fine drawings of the principal specimens of Angelin's genera, embracing all the types figured in the *Iconographia Crinoideorum* that can be found, and some other specimens not heretofore figured. These drawings, made with the unrivaled skill and care which characterize all of Liljevall's work, have made clear some points hitherto obscure on account of the notorious inaccuracy of Angelin's figures, and have also led to some unexpected results. In view of the importance of some of these observations, and their bearing upon the classification of this group, I have thought it advisable to publish a brief account of them now as a preliminary note to the work upon it which I have in preparation.

It was shown in the paper above cited that in the family Taxocrinidae there is a progressive variation in the position of the radianal, similar to and somewhat parallel with that observed in the Inadunata, viz.: from a primitive position directly under the right posterior radial, to an oblique position under the lower left corner of that radial in the Silurian, and finally to complete elimination in the Carboniferous. It now appears that there is a similar variation and succession in the position of the radianal among the Ichthyocrinidae. *Anisocrinus* and *Clidochirus* prove to have a large radianal; in the latter in a radial position directly underneath the right posterior radial, as if it were the lower half of it, as in *Temnocrinus;* while *Lecanocrinus* and *Pycnosaccus* have it smaller, and located obliquely under the left part of the right posterior ray, as in *Gnorimocrinus*. *Homalocrinus* also has the radianal in the primitive position, but it is smaller than in the two first-named genera. In *Mespilocrinus* and other carboniferous forms it has disappeared altogether.

The greatest surprise, however, has been to find a somewhat similar condition among forms which have been referred to the genus *Ichthyocrinus*. The genus has been heretofore considered by everybody as the simplest of all, having a perfectly symmetrical calyx,

without anal or interbracial plates, and persisting in this simple form from the Silurian to the Carboniferous. It now develops that this is not true for the Silurian species. Liljevall, while making the drawings for me above referred to upon specimens in the Museum at Stockholm, called my attention to the fact that in all Gotland *Ichthyocrini* the right posterior ray has an extra plate, just like *Temnocrinus tuberculatus*. By cleaning the base of some specimens so that the infrabasals could be seen, he was able to locate the right posterior ray by its being in line with the small infrabasal. It was in this ray that the extra plate was invariably found, smaller than the radial, sometimes visible laterally and sometimes hidden by the column. Here, evidently, was also the radianal in its primitive position. I have much pleasure in according to Mr. Liljevall the credit for this sagacious observation of a fact which had escaped the notice of all of us.

This at once suggested the idea that probably the same thing would be found in the Silurian *Ichthyocrini* from England and America; and an examination of the published descriptions immediately furnished abundant indications of it as to the American species. Hall's figures and diagrams of *I. laevis*,[1] and of *I. simplex*[2] show an extra plate in one ray. So also do his figure of *I. subangularis*,[3] and Ringueberg's figure and description of his *I. conoideus*.[4] A similar condition was indicated in Weller's description of *I. subangularis*,[5] where he says the radials are "generally unequal," and "costals two, rarely three, in each ray." In all of these there appeared to be in one ray four primary plates, instead of three as in the others, though in none of them was the position of the infrabasals accurately shown, so as to determine which ray possessed the extra plate. Indeed, without special preparation the infrabasals cannot often be seen in this genus. Nevertheless, with the facts shown by the Swedish specimens, there seemed no reason to doubt that the irregular ray was here also the right posterior.

[1] *Palæontology of New York*, Vol. II, Plate 43, Figs. 2*a* and 2*e*.

[2] *Ibid.*, Plate 46, Fig. 2*e*.

[3] *Twenty-eighth Report*, New York State Cabinet of Natural History, Plate XVI, Fig. 13.

[4] *Annals*, New York Academy of Sciences, Vol. V, No. 6, p. 301.

[5] *Bulletin IV*, Chicago Academy of Science, p. 146.

These observations suggested also the idea that, if this should prove to be the fact in the Silurian and not in the Carboniferous species, then we should have a further and most interesting example of evolution in the elimination of the radianal from Silurian to Carboniferous times, within what has been considered as a single genus. With a view to ascertaining the facts definitely, I undertook a careful examination of my specimens, with additional preparation, sometimes grinding off part of the base to expose the infrabasals; and I have also since then had in hand for study good specimens from the Niagara of Canada and New York, most obligingly loaned me by Mr. Byron E. Walker, of Toronto, and Dr. E. N. S. Ringueberg, of Lockport, N. Y. This examination gave the following results:

Silurian Species

I. pyriformis (?), from the Wenlock Limestone, Dudley, England: In a large and quite perfect specimen I removed the stem, and by grinding succeeded in exposing the infrabasals; along with which appeared a radianal under the right posterior radial. This is invisible in a side view, but appears on the flat part of the base, only half as large as the radials in the other four rays (Plate IV, Fig. 3). Another specimen of true *I. pyriformis* in my collection, and three others since examined in the British Museum, show the radianal.

I. laevis, from the Niagara: Eight specimens from New York and Canada show infrabasals and radianal (Plate VI, Fig. 1).

I. subangularis, from the Niagara: Five specimens from Indiana and Illinois show infrabasals and radianal (Plate VI, Fig. 2); and numerous others among the casts of *I. corbis* found at Milwaukee and Chicago which do not preserve the infrabasals, distinctly show the impressions of the radianal.

Carboniferous Species

I. burlingtonensis, Lower Burlington Limestone: Six specimens preserving the rays all around show uniformly a radial and two primibrachs, without any sign of a radianal (Plate VI, Fig. 15). Two of them have the infrabasals well preserved, one both externally and internally.

I. tiaraeformis, Keokuk Limestone, Tennessee: Besides the type,

I have five specimens suitable for this study—two from the original locality at White's Creek Springs, Tenn., and three from near Louisville, Ky. Four of them have all the rays visible, and they all show perfect symmetry below the first bifurcation, the rays having uniformly the radial and two primibrachs, without any radianal. In these specimens there is some irregularity in the secundibrachs, one having 4–4 in all rays, and the others having 4–4 in some rays and 4–3 in others. In another specimen the rays are not fully preserved, but the condition is such that, in addition to the radials and some primibrachs, they show the basals and infrabasals very plainly, both internally and externally, and there is no radianal. In the type specimen, however, from the Troost collection in the National Museum at Washington, which preserves all rays intact, there is an extra plate in one ray, which has radial and three primibrachs, while all the others have two primibrachs, with variations of 4–3 to 4–4 secundibrachs. The infrabasals are not visible, and it is impossible to judge whether the extra plate is in the right posterior ray or not. The lower plate in the ray having the extra one is of the same size and shape as the lower plate in the other rays, and does not exhibit the difference which characterizes it in the Silurian specimens. In view of the uniform absence of a radianal in all other Carboniferous specimens, I think we are warranted in considering the presence of an extra plate in this one as a case of sport—just as we have in some specimens an occasional straggling interbrachial.

In *I. greenei*, from the Keokuk Limestone of Indiana, only three rays are visible, each of which has the radial and three primibrachs.

What the condition of the genus was in the Devonian we do not know. It is supposed to occur in the Chemung of New York, but all the specimens that I have seen are too imperfect to afford any information. If any reader of this paper should possess a specimen of *Ichthyocrinus* from the Devonian, with the base or all five rays preserved, I should esteem it a great favor to be advised of the fact.

The result, therefore, of the examination of actual specimens considered to be *Ichthyocrinus* is:

1. All Silurian specimens, without exception, have a radianal in primitive position under the right posterior radial.

2. All Carboniferous specimens (with the solitary exception above

noted) have a perfect pentamerous symmetry below the first bifurcation, and thus have no radianal.

Hence we have in this form an evolution from the Silurian to the Carboniferous, just as is found from

Sagenocrinus to *Forbesiocrinus*,
Gnorimocrinus to *Taxocrinus*,
Clidochirus to *Mespilocrinus*.

The process here shown, substantially parallel with what takes place in the Inadunata, is the elimination of the radianal in paleontological time by rising, or being lifted upward, from beneath the radial, analogous to the migration and disappearance of the anal plate in the larval stages of *Antedon*, of which I shall have more to say later on. If these views are correct, it follows that the Carboniferous form should be separated generically from the Silurian. As *I. laevis*, from the Niagara, is the genotype of *Ichthyocrinus*, it seems proper to retain the genus for the Silurian species and any other that may prove to have a radianal. I therefore propose for the Carboniferous form, and all that may be without a radianal, the genus *Metichthyocrinus*.

As already intimated, *Anisocrinus* and *Clidochirus*, two of Angelin's Silurian genera, also prove to have an unsymmetrical calyx, owing to the presence of a radianal underneath the right posterior radial. In *Clidochirus* it is directly under the ray, in the position of an interradial (Plate VI, Fig. 7). This is shown in Angelin's figure of *C. pyrum*.[1] The original to his Fig. 6, Plate XVII, which is a restoration from an imperfect calyx, and incorrectly drawn as to the part preserved, is a right anterior view of a weathered specimen of this species; the lower part of the calyx, showing the anal side, is figured herewith (Plate VI, Fig. 8). There is also a third specimen in the Stockholm collection which shows the characters perfectly (Plate VI, Fig. 7). The difference between the two genera is that *Anisocrinus* has the interbrachials all around, while *Clidochirus* has none except at the anal side. The radianal of *Anisocrinus* is not quite so regular in its position as in the other genera having this structure. In *A. interradiatus* it is large, and well underneath the radial. Angelin's figure of his only specimen, Plate XXII, Fig. 18, does not show any

[1] *Iconographia Crinoideorum*, Plate XXII, Fig. 23.

radianal, but it is perfectly developed in the specimen (Plate VI, Fig. 9), and also in another one since found. In *A. angelini* W. and Sp. (figured by Angelin as *Lecanocrinus macropetalus*) his first specimen[1] has no radianal, and the figure is correct in this respect; but the second specimen[2] has a very distinct radianal, situated obliquely under the left corner of the right posterior radial; while in a third specimen, found since Angelin, the radianal is large, and fully under the radial (Plate VI, Fig. 10). It is quite possible that the first specimen does not belong to this genus, as there is some difference also in the arms.

These two genera differ from *Homalocrinus* and *Calpiocrinus* in having very large basals. It is interesting to note that both of them occur in America. *Lecanocrinus greenei* of Miller and Gurley,[3] and *L. oswegoensis*,[4] both belong unquestionably to *Anisocrinus*. Miller and Gurley's figure of *L. greenei* shows nothing of the radianal, which is plain enough in the specimen, cut off from the lower left part of the right posterior radial (Plate VI, Fig. 11); but in the other species it is shown in their Fig. 16 (Plate VI, Fig. 12). The *Clidochirus* is an undescribed form from our western Silurian.

Liljevall's drawings also enable us to understand the rare genus *Calpiocrinus*, which turns out to be a very curious and extraordinary affair (Plate VII, Figs. 1–8). Angelin described it as having three basals and no parabasals, or, as we should say now, three infrabasals and no basals. Wachsmuth and Springer[5] were much puzzled by the fact that this genus, as described by Angelin, seemed to have but one ring of plates below the radials; but expressed the opinion that this ring of plates "is the analogue of the underbasals, and that the true basals, if not absent, are exceedingly rudimentary." Dr. Bather, on the other hand,[6] states that *Calpiocrinus* "has minute, often obsolete IBB, but fairly large BB." The facts now disclosed show that Angelin's description was wrong; but that Wachsmuth

[1] *Ibid.*, Plate XIX, Fig. 3, and Plate XXII, Fig. 24.

[2] *Ibid.*, Plate XIX, Fig. 4.

[3] *Bulletin No. 8*, Illinois State Museum, Plate III, Fig. 28.

[4] *Ibid.*, No. 4, Plate III, Figs. 15, 16.

[5] *Revision of the Palæocrinidæ*, Part I, p. 38.

[6] Lankester's *Treatise on Zoölogy*, Part III, p. 189.

and Springer's interpretation of the conspicuous ring of plates was substantially correct. As a matter of fact, there are two rings of plates below the radials—i. e., both infrabasals and basals; but the remarkable thing about it is that the infrabasals are developed to an extent and in a manner unknown in any other Crinoid. In many dicyclic forms the infrabasals lie within the ring of basals, abutting against them by their lateral faces; and they are naturally subordinate in size and position. But here they overlap the basals to such an extent as to sometimes wholly conceal them, and not only them, but also the radials, and even part of the first primibrachs (Plate VII, Fig. 6). In some cases two or more of the basals are visible as mere points (Plate VII, Figs. 3, 8); but usually only the posterior basal projects (Plate VII, Figs. 2, 4). In one specimen no basal at all is to be seen, and the large infrabasals appear externally to be directly surrounded by the radials (Plate VII, Fig. 5).

The three unequal infrabasals form a relatively enormous growth, far exceeding in size the basals, and enveloping them somewhat after the manner of the centrodorsal in *Thiollericrinus* and other Comatulae. The actual relation of the two sets of plates is shown in specimens like Fig. 6, Plate VII, where the infrabasals have been partly removed, and the basals become plainly visible beneath them, five in number. Thus the basal elements of the calyx are the same as in the group generally—3 IBB, and 5 BB—and the small infrabasal is usually located, as it should be, under the right posterior ray. In addition to the information furnished by Liljevall from the specimens at Stockholm, I have several good specimens of this genus in my own collection, which fully confirm the foregoing observations. There remains no longer any doubt of its real structure, and the genus must therefore be considered as representing a definite, though extravagant and therefore short-lived, modification of the Crinoid plan, in a direction not heretofore noted.

This condition seems to be an exaggeration of that which obtains in many of the Flexibilia, where the infrabasals have a tendency to overlap the basals like a column plate, as in *Forbesiocrinus* and *Taxocrinus*. In these cases the union with the column seems to be stronger than with the calyx; the infrabasals are frequently fused with the top columnal, and remain firmly soldered to it when the column is

detached from the calyx.[1] That is what has happened in the specimen figured herein (Plate VII, Fig. 20), where the infrabasals have separated from the calyx in this manner. This feature is the result of the general fact, discovered by Wachsmuth and Springer,[2] and accepted by subsequent authors, that in the Flexibilia generally the top columnal is not the latest formed, as in the Camerata and most Inadunata, but remains as a persistent proximale. This has been believed to be a fundamental character, evidencing the independent nature of the group—though the proof of its universality is, in my opinion, not complete, and there are apparent exceptions to it. The remarkable example of regeneration mentioned by me in my former paper on this subject,[3] where the calyx of a *Taxocrinus* was restored by new growth upon the infrabasals and one basal, is strongly confirmatory of this idea, and suggests that in this group the axial organ as the seat of vitality in the animal, was located very low in the calyx—i. e., within the infrabasals and extending down into the proximal part of the column.

Homalocrinus, which Angelin founded on a single species, *H. parabasalis*,[4] is of a similar type, but the basals are larger and not so much concealed by the overlapping infrabasals (Plates VII, Figs. 9, 10, 11). I was at first disposed to consider it as congeneric with *Calpiocrinus*, until Liljevall's careful study of the type specimen brought to light a small radianal lying beneath the right posterior radial. Then it occurred to me that this was the condition of certain specimens from the Wenlock Limestone of Dudley, England, which had for a long time puzzled me—and for which in my former paper I had suggested the name *Leiocrinus*—and that they would fall nicely under *Homalocrinus*. They accentuate the differences between *H. parabasalis* and *Calpiocrinus*, having larger radianal and more prominent basals. I give figures of two of the specimens (Plate VII, and Figs. 12, 13), and propose for them the name *Homalocrinus dudleyensis*. So far as I know, these two genera are the only Crinoids in which such a peculiar development of the infrabasals is found.

There is a notable difference between them in the arm structure—

[1] *North American Crinoidea Camerata*, Plate II, Fig. 4*b*.

[2] *Ibid.*, p. 39. [3] *American Geologist*, Vol. XXX, p. 97.

[4] *Iconographia Crinoidarum*, Plate XVI, Fig. 20.

Calpiocrinus having twenty main arm branches or trunks, about equal, each pair bearing ramules inside the dichotom; while *Homalocrinus* has ten such main branches. The first, or lowest, ramule is usually the largest, and may sometimes branch again. Variations in this respect give rise to intermediate forms, and while well-marked specimens of the two genera are strikingly distinct, it is easy to see how the two arm characters shade into one another. In *C. fimbriatus* (Plate VII, Fig. 1) it will be seen that the ray bifurcates into two equal divisions, and each of these divides again into two main branches or trunks of about equal size, from the inner side of each of which are given off three or more lateral ramules. In *H. parabasalis* (Plate VII, Fig. 9) and *H. dudleyensis* (Fig. 12) the first bifurcation in the ray produces two main arm branches having similar ramules, of which the lower one is the largest. If this lower ramule increases further, until it approaches the size of the outer branch, and also begins to give off in turn subordinate ramules, then we shall have the condition, approximately, of Fig. 1. Thus we may expect to find intermediate stages of this progression; and when the lower ramule of the ten-branched form becomes considerably enlarged, we are in doubt whether upon this character to call it *Homalocrinus plus*, or *Calpiocrinus minus*. And then comes the old question: Shall we throw them all into one genus because of the connecting links, or maintain the genera upon their typical forms? Of course, the correlation of the radianal, if present, will avoid this difficulty; but I find this to be quite unequally developed in the English forms of *Homalocrinus*, and it is probably so in the Swedish—being so small in the type specimen of *H. parabasalis*. In the former some of my specimens have it only half the size of the radial, some about equal to it; and in some, not otherwise distinguishable, I cannot see it at all. I think the difference in this respect may be partly due to the unequal development of the infrabasals, which may sometimes conceal the radianal, which in this form is located wholly within the ring of basals, as in *Sagenocrinus*. This may also be considered as an interesting case showing how, under the influence of an extravagant modification, characters otherwise important were greatly overshadowed, and a close and rapid transition occurred, tending to produce an intermingling of such characters.

Phillips' genus *Eurycrinus*, which has been heretofore considered

a synonym of *Ichthyocrinus*, may now be assigned a definite place in the analysis of the genera. Thanks to the courtesy of Dr. Bather, I have recently had the opportunity to examine the type specimens, now in the British Museum; and they demonstrate very clearly the generic distinctness of this form. It has the regular dicyclic base of the Flexibilia, with 5 BB and 3 IBB—the latter more or less atrophied, or resorbed by the very large axial canal; and it has a series of large anal plates, completely filling the posterior area, together with a small development of interbrachial plates. It has the habitus of the *Ichthyocrini*, and stands close to *Parichthyocrinus*, from which, however, it is well distinguished by the anal structure.

I am also now enabled, by the aid of Liljevall's drawings and some interesting specimens in the British Museum, to treat more definitely the genus *Pycnosaccus*, which was formerly placed as a probable synonym under *Lecanocrinus*. It has fairly large interbrachial areas, which are apparently without well-defined plates, such as are in *Anisocrinus*, but were evidently filled by small, irregular plates which are not preserved in any of the specimens thus far seen. The calyx as observed is strong, and much wrinkled or folded exteriorly. It also frequently has but a single primibrach.

Cleiocrinus, from the Lower Silurian of Canada, which was before arranged with this division of the Flexibilia, may now be left out of it, except as a probable transition form. From an investigation I have recently made of all the known material, this proves to be an even more extraordinary and anomalous genus than *Calpiocrinus*, being probably an intermediate form between the Camerata and the Flexibilia. It has the pinnulate arms and five infrabasals of the dicyclic Camerata, combined with the pliant calyx, with plates united by loose suture, of the Flexibilia.[1]

I exclude from the list of Flexibilia the genus *Rhopalocrinus*, which may be considered as an intermediate form between the Flexibilia and the Inadunata. It has a strong ventral tube, rising high up between the arms. It lacks the pliant calyx of the former group, but rather resembles a dicyclic Symbathocrinoid, and would readily fall under the Inadunata but for the presence of a slightly developed interbrachial system.

[1] *Memoirs*, Museum of Comparative Zoölogy, Harvard, Vol. XXV, Part 2.

Professors Waagen and Jahn, in Vol. VII of the *Silurian System of Bohemia*, have described a new genus, *Caleidocrinus*, from Stage d 4 of the Bohemian section, which they place near the Taxocrinidae of Angelin, and which Mr. Bather[1] assigns to the Flexibilia Impinnata, and considers to be "a genus that approaches the common ancestor of *Ichthyocrinus* and *Taxocrinus*." Through the kindness of Professor Jahn, who made a special trip to the locality near Zahoran for me, I have been favored with some specimens of *C. multiramus* in as good condition as they are usually to be obtained. They occur in a schist, and all specimens thus far found are so flattened by pressure that none of them show all five rays, and I doubt if it is certain whether the anal side is distinct or not. The condition of preservation is such as to render observation on some points very uncertain. Messrs. Waagen and Jahn[2] say of this:

> The skeleton and elements constituting the body of these sea lilies are changed into a ferric hydrate. By reason of this change there exist only the negative impressions of half the calyx, which are filled with a powder of ferric hydrate.

They state that the figures on Plate 63 are very defective, and they give other figures in the text, partly of the same specimens and partly from better specimens. Even of these text-figures, however, they say on p. 109:

> The preservation of the interradius (*ir*, Figs. 276—316 of the text), and of the anal interradius (*a*, Figs. 276–316 in the text), is so defective that if we can, in some cases, observe the position of the plates which compose them, it is never possible to determine their number.

I have six good specimens in the condition described by the authors, viz., impressions in the matrix filled with powder of iron oxide; and one rather larger than usual in which, by rare fortune, the skeleton of the Crinoid is preserved intact. I have also wax casts of the specimens from which Figs. 1–2 and 11–14 of Waagen and Jahn's work were made, kindly sent to me by Professor Dr. Perner, of the Royal Museum at Prague. In none of these have I been able to identify satisfactorily any interbrachial (interradial) or anal plates. Not having seen all the specimens on which the figures are based, I do not deny the existence of such plates; but I wish to suggest

[1] *Annals and Magazine of Natural History*, July, 1900, p. 112.

[2] *Op. cit.*, p. 107.

that in specimens preserved as these are it is extremely difficult to determine such structures with certainty. Many foreign bodies may become lodged between the rays which might, in the chemically changed condition of the fossils, be mistaken for small, irregular plates. One may even mistake for interbrachials what may be only fragments of arms, as has actually occurred in one case I know. In my specimen with the substance of the Crinoid preserved the radial and brachial plates are well defined, and there is certainly no sign of any plates meeting their margins between the rays. Assuming them to exist, however, as figured by the learned authors, they may be taken to form part of a flexible integument, and the structure would be in a condition analogous to that of the Carboniferous genus *Nipterocrinus*, although otherwise there is no resemblance between them.

Nothing is known of the base; whether it is dicyclic or monocyclic cannot be ascertained from the specimens. The habitus of this form seems to me rather like that of the Inadunata, from which it is separated only by the supposed interbrachial structures. It is certainly a strange and interesting genus, as to which we may well wish for more information. If it had been found in the Jurassic, instead of the Ordovician, I think no one would have hesitated to place it among the Pentacrinidæ.

Dr. Bather bases his conclusion as to the ancestral character of this form upon the statement that it is "older than any flexible genus hitherto known, and the interest is enhanced when we see how its structure accords with its age in the eyes of the evolutionist;" and that "Flexibilia have not hitherto been known earlier than the Wenlock age." In making this statement he must have overlooked the specimens of *Taxocrinus* described by Billings under *Lecanocrinus elegans* and *L. laevis*,[1] which are much older than the Wenlock, and at least as old as the stage of *Caleidocrinus*. They occur in the Trenton Limestone of the Lower Silurian, or Ordovician, at a horizon which has been considered by geologists as substantially equivalent to the Bala of England, which Bather takes to be about equal to the Stage d 4 of Bohemia. And it is, of course, much older than the Wenlock, which is the age of the Upper Silurian, approximately equivalent to the Niagara of America.

[1] *Canadian Organic Remains*, December, IV, Plate IV, Figs. 3, 4.

In the second family group, as formerly defined, subsequent observations have led me to make some important modifications of the arrangement heretofore proposed by me. It has long seemed desirable to find some basis for separating the Silurian species of *Taxocrinus* from the Carboniferous. Considering the changes that have taken place in other types of this group, and especially since the discovery of the facts above stated as to the *Ichthyocrini*, it seemed to me to the last degree improbable that such a form as *Taxocrinus* should persist from the Lower Silurian to the latest Subcarboniferous, without any modification of more than specific importance. Yet upon the basis of any of the characters hitherto regarded as important in this group I was unable to find satisfactory ground for distinction. I was at first strongly disposed to believe that the Gotland species must all, if correctly observed, prove to have an unsymmetrical calyx—that is, with a radianal—and thus belong to *Gnorimocrinus*. But a careful re-examination by Mr. Liljevall of all the specimens at Stockholm, with detailed drawings of each, has convinced me that Angelin's *T. rigens* and *T. oblongatus* have no trace of a radianal. The type specimens of *T. elegans* and *T. laevis*, from the Lower Silurian of Canada, do not show the anal side, but when discovered I should expect to find a radianal.[1]

Finally, however, the solution presented itself in a very simple matter, which has been overlooked hitherto in all researches upon the classification of this group, but which, upon consideration, appears to be of considerable importance. It lies in the condition of the rays below the first bifurcation—that is, of the brachials of the first order. On account of some irregularity in a few cases noted by early observers, it has been handed down as a tradition, and religiously observed, almost since the time of Phillips, that such irregularity in the branching of the rays was a characteristic of the whole group. This fact seems to have diverted attention from the real significance of this structure. In the *Revision of the Palæocrinoidea* this opinion was expressed, and in proof of it allusion was made to the differences in the rays of *Ichthyocrinus*, which are discussed herein, and shown to

[1] Since the above was written, specimens of both species have been found showing the posterior side, and each has a large radianal in primitive position under the right posterior ray.

be due to the presence of a radianal uniformly in one ray; and to the case of *Forbesiocrinus agassizi*, which will be considered later. I have often heard Wachsmuth emphasize the statement that not only are there irregularities in the rays, but that such irregularity was a positive character of the group.

If we take a specimen like *Taxocrinus affinis* Mueller,[1] we see that the ray bifurcates on the second plate above the radial; or, in other words, the ray has two brachials of the first order, or primibrachs. Examining then the figure of *Taxocrinus splendens* M. and G.,[2] from Crawfordsville, Ind.—the best known Carboniferous species, and found under other names in collections the world over—we shall find that the bifurcation of the ray occurs on the third plate above the radial; that is, it has three brachials of the first order, or primibrachs. The first of these plans is that which prevails throughout the Camerata, with a few exceptions, some of which can usually be explained by the anchylosis or syzygial union of two plates. It now proves to be a fact that it is also the structure of almost every one of the Silurian and most of the Devonian forms of the Flexibilia, with a very few exceptional cases, some of which I believe may be traceable to abnormal specimens. It follows feebly down into the Carboniferous in the genera *Synerocrinus*, *Wachsmuthicrinus*, *Mespilocrinus*, and *Metichthyocrinus*, all of which are rare fossils. It ceased in the Paleozoic, so far as we know, with the Keokuk Limestone, nothing of that form having been seen from the Warsaw, St. Louis, or Kaskaskia, beyond a few individually exceptional cases. Afterwards it appears to have resumed its sway in the group, for it prevails through the Mesozoic and to the present time in the great genera of the Flexibilia Pinnata—*Apiocrinus*, *Millericrinus*, *Uintacrinus*, *Antedon*, and *Actinometra;* the two primibrachs in the later two genera being sometimes united by syzygy.

The second plan, while it may be exceptionally indicated by a few cases in the Silurian and Devonian, became the leading feature of the Carboniferous Flexibilia, where it is conspicuous in numerous species of the widely distributed genera *Taxocrinus* and *Forbesiocrinus*, from the Waverly to the Kaskaskia; *Parichthyocrinus* in the

[1] *Mon. Echinod. Eifler-Kalkes*, Schultze, Plate 4, Fig. 2.

[2] *Bulletin No.* 8, State Museum of Illinois, Plate 5, Fig. 3.

Burlington and Keokuk; until the culmination of the group in *Onychocrinus*, some species of which regularly add another primibrach. It prevailed exclusively during the Warsaw, St. Louis, and Kaskaskia, after structure No. 1 had disappeared.

Occasional abnormal specimens occur in these genera, but they are rare, and no more than might be expected to occur in a structure so powerfully modified as this. In order to test the possible importance of these exceptions, I tabulated the facts as observed in two abundant species, representing the two leading genera of plan No. 2, with three primibrachs, viz., *Forbesiocrinus multibrachiatus* L. & C. (not the Crawfordsville species erroneously so labeled in many collections, but from a different horizon and locality), and *Taxocrinus spendens* M. & G. (which is the well-known Crawfordsville species labeled in some collections *T. multibrachiatus*, and in some *T. Meeki*). Both were prolific species, flourishing abundantly in two different horizons and localities—thus furnishing the right conditions to show irregularity if it exists. Of these I have a large number of specimens in which five rays are exposed. In thirty such specimens of *F. multibrachiatus*, ranging from very young to adult, all have the regular three primibrachs throughout, except three specimens, which have two primibrachs in one ray. In *T. splendens*, out of eighty-nine specimens—

77 have the regular	3 IBr throughout,
4 have	4 IBr in one ray,
6 have	2 IBr in one ray,
2 have	2 IBr in two rays.

All other rays of these are regular.

Variations as great as this are to be found in the strongest characters of almost any group in nature. Out of a large number of *Pentremites godoni* I have no less than thirty-two specimens with only four rays, and seven with six rays. I have a *Taxocrinus*, otherwise perfect, which has only four rays—there being no sign whatever of a fifth. The seeker after good luck will find by diligent search more four-leaved clovers than he will exceptions to the regular brachial arrangement of *Taxocrinus* and *Forbesiocrinus*.

The case of *Forbesiocrinus agassizi* has been cited as a decisive example of irregularity in this group, being said to vary from one to

three primibrachs. I have never seen a specimen with only one, although it might happen as a mere abnormality; but the case is a most interesting one upon the actual facts. This species, from the Burlington Limestone, systematically and regularly departs from the brachial arrangement of all other described *Forbesiocrini*, in having but two primibrachs. It is a rare species, and specimens are especially rare in which all rays are exposed; but usually at least three are visible, enabling us to see the prevailing type. I have thirteen specimens, and have observed seven in other collections, all of which show two primibrachs in the visible rays. There is another form occurring still more rarely in the Burlington Limestone which has the normal arrangement of three primibrachs. It is considerably smaller than *F. agassizi*, but strongly resembles it, and has hitherto been assumed to belong to it. It might be treated as of the same species, which would thus exceptionally embrace representatives of structures elsewhere widely distinct; or, what is perhaps the more rational view, good reason may be given for separating *F. agassizi*, both specifically and generically.

In *Taxocrinus* also there is some irregularity of this kind among certain Devonian species; that is, some individuals have two primibrachs, while others of apparently the same species have three. In a specimen of *Taxocrinus intermedius* from the Kinderhook two rays are irregular, and in the type of *T. nobilis* from the Mountain Limestone, one. Here the Devonian and Lower Carboniferous may be considered the transition period, in which the three primibrachs were being established in the genus. There is also to be seen in occasional specimens in the Kaskaskia a tendency toward reversion to the two-primibrach structure.

Ichthyocrinus greenei, of the Keokuk Limestone, is the only example of *Ichthyocrinus* or its carboniferous representative with three IBr in more than one ray. It is known only from a single specimen, which does not expose the anal side; and we cannot be certain of its generic relations, notwithstanding its close superficial resemblance to the typical *Ichthyocrini*.

I am not concerning myself, however, with the few exceptional cases which may be found; but if anyone will examine such a series of the four leading genera above mentioned as I have before me, with hun-

dreds of specimens of wide geographical distribution and great vertical range, he will see that there is not the slightest doubt of the validity of the distinction between the two plans of structure. If irregularity in the rays were a prevalent character, we would expect, in species of many genera, numerous variations in the number of primibrachs in different rays of the same individual. But we do not find the number varying indiscriminately among the rays; as a matter of fact, such cases are extremely rare. Besides those above noted, I have seen such variation in scarcely a dozen specimens among all the genera, and these are mostly confined to a single ray. We do not find, to any appreciable extent, intermediate forms—not, indeed, so many as might be expected. *Lecanocrinus*, and its allied form *Pycnosaccus*, exhibit some irregularity in a tendency to a single primibrach instead of two. The few known specimens of *Pycnosaccus* vary from one to two plates, both in the primibrachs and secundibrachs. The Silurian species of *Lecanocrinus*, in which the rays are preserved in many specimens, show very few exceptions to the rule of two IBr; but in the Devonian, on the eve of the extinction of the genus, there appears to have been more variability, although our materials for testing it are very meager. Of Schultze's *L. roemeri*, in the only two specimens I know preserving the arms, the number of IBr varies as follows: No. 1, 2–1–1–1–1; No. 2, 2–1–2–2–1. There is also a specimen from the Silurian of Sweden, something like *Calpiocrinus*, which has one IBr all around except in the posterior ray, where an additional one appears, perhaps a radianal. These cases may be explained by supposing the two IBr to have been coalesced by syzygial union, as occurs among the living Comatulae. In *Onychocrinus ulrichi* there is some variation from the rule of four IBr, some rays having three, and others five. This was at about the extinction of the group, of which *Onychocrinus* represents the most extravagant development.

Of course in the Silurian those species with a primitive radianal have a partial equivalent of three IBr in the right posterior ray; but that is constant, and is otherwise accounted for; and it does not affect the rule which prevails throughout the four regular rays. What was the morphological process by which this modification took place, I am unable to explain. The developmental history of

the group indicates a tendency to get rid of the extra plate in the right posterior ray, if we have been right in considering that plate—both in this group and in the Inadunata—as a radianal. But the change was not characterized by any indiscriminate individual variations; it must have taken place directly from one structure to the other, through mutations in species and genera. Out of twenty-six specimens of *Temnocrinus tuberculatus* showing the posterior ray, but a single one fails to show the radianal as I have described it.

In the Silurian, the plan of two IBr prevailed almost exclusively—only two generic forms, represented by *Gnorimocrinus loveni* in Sweden, and *Taxocrinus orbignii* in England, having three IBr throughout. One abnormal specimen of *Gnorimocrinus expansus* has three IBr in one ray, and one of *G. tubulijerus* has it in at least three rays. So far as I know, these are all the exceptions in the Silurian. The change was more notable in the Devonian, where some species have both two and three IBr and about one-third of the species heretofore referred to *Taxocrinus* appear with three IBr throughout. The *Taxocrinus* with two IBr persisted into the base of the Carboniferous with one or two species in the Kinderhook and Waverly; but from there on the three IBr structure became universal in this and related genera. The few exceptional cases we know in individual specimens do not fill the gap between the two structures. It was a decided morphological change, affecting the entire brachial system, and as to the *Taxocrini* it took place chiefly in the Devonian.

It follows from these considerations that the Silurian and most of the Devonian species of *Taxocrinus* should be separated generically from those of the Carboniferous. Since *T. tuberculatus* has been removed to form the type of *Temnocrinus*, on account of the possession of a radianal, there remain three species originally referred to the genus by Phillips: *T. nobilis*, *T. macrodactylus*, and *T. egertoni*. In discussing them under his first name, *Isocrinus*,[1] he says that *T. nobilis* and *T. macrodactylus* have four "costals." It is clear that he includes what we now call radials and primibrachs, for on p. 29 he says: "the pentagonal columnar joint is surmounted by five plates (the pelvis of Miller), alternating with which, and above them, are

[1] *Pal. Foss. Cornwall*, p. 30.

five rows of broad costal and scapular plates, four in each, the last being cuneiform." As *T. nobilis* and *T. macrodactylus* have hitherto been taken as the typical forms of the genus, and according to Phillips' diagnosis they possess the brachial structure No. 2, it seems proper to retain the name for the Carboniferous species and such Devonian or Silurian ones as prove to have this structure. For those species of *Taxocrinus* having the original structure of two primibrachs I propose the genus *Eutaxocrinus*, including provisionally the Silurian *T. oblongatus* and *T. rigens*, which are probably one species, and tend toward *Dactylocrinus* in the arm structure.

In attempting to arrange the genera of the Flexibilia into families, or other subgroups, we have to choose between several kinds of modification on which to base them. We know the life-history of one genus of the Flexibilia Pinnata, viz., *Antedon*. Considering that to represent, in a general way and to some extent, the phylogenetic history of the group, we may assume that its ancestral form would be something like the early larval stage of *Antedon*, with the addition of a radianal, of which no trace or suggestion has yet been found in the embryological researches on that genus, as I understand them. This would give us a dicyclic Crinoid, with a radianal; an anal plate between the posterior radials; two primibrachs, the second one axillary and followed by arm branches; and the ventral side surmounted by a closed pyramid of oral plates. I have attempted to represent the dorsal side of such a hypothetical Crinoid by Fig. 9 on Plate II. The lines of modification from such a form on the dorsal side would be:

a) In the radianal, by migration upward.

b) In the anal system by (1) extension upward in vertical series not connected with brachials, and replacement laterally by perisome; (2) increase upward and laterally in connection with the brachials; (3) elimination of the anal plate.

c) In the brachial system by (1) increase in the number of primibrachs; (2) variation in the mode of branching of the higher brachials or arms.

d) In the interbrachial system, by growth and multiplication of supplementary plates between the rays.

On the ventral side we might expect modification in the same way that we see in *Antedon*, viz., a growth of perisome between the radials and orals, gradually separating the latter plates from the raidals and carrying them inward toward the center. This would give the condition found in *Onychocrinus* and *Taxocrinus;* but the cases in which these structures are preserved in the fossils are too few to enable us to trace any of the successive changes.

a) The first of the above modifications of the dorsal side has been already discussed, both in this and my former paper; and it has been shown that there are to some extent parallel modifications of this character in the two families as formerly defined, which might form the basis of some lesser groups. But the radianal was early eliminated in this group, being known only beyond the Silurian in two Devonian species, and modifications on this line do not cut much figure in the delimitation of the families. There are still some troublesome questions of interpretation among the Swedish species, owing to irregularities. Several of them are represented by only a single specimen, and this in some cases abnormal. These cases will be left for consideration hereafter in greater detail, in the hope also that the discovery of further specimens will throw new light upon them.

b) The generic distinctions based upon the other modifications of the posterior, or anal, area, coming under the second category, are really very striking—more so than can be well expressed in terms of brief analysis. Aside from the matter of the radianal, there are two plans of structure of the anal area, which run side by side from the Silurian to the Carboniferous. They start with the primitive anal plate of our supposed ancestral form, and diverge upon the two lines 1 and 2 indicated above.

1. The first of these plans is one which represents a solid support or backing of an anal tube. It is marked by a vertical row of strong, rounded plates, originating on the posterior basal, rising with a very gradual taper to a considerable height between the rays, and having the appearance of a small, rounded arm. It is connected with, or rather seems grown into, the pliant integument of small, irregular plates which formed the perisome, or ventral covering in this group.

As I have shown by the tegmen of *Onychocrinus*, the perisome developed between the radials and the orals, carrying the latter relatively inward until, instead of covering the whole ventral side as in the very early *Antedon* (Plate V, Fig. 3), they occupied only a small space in the center of the disk, into which the ambulacra converged after traversing the perisome (Plate IV, Fig. 1). In the present modification of the anal side it would seem as if the perisome began to grow with similar energy toward the dorsal side and down between the rays, so that it encroached upon the anal plate on either side as far as the posterior basal; while the upward extension of that plate took the form of a simple vertical series of rounded plates. Hence this armlike row of anal plates is usually found, in well-preserved specimens, bordered upon one or both sides by small, irregular plates, which were a part of the perisomic integument lying between them and the adjacent rays (Plate IV, Fig. 5). This plated integument, in addition to being pliant, was also very fragile, and its preservation in the fossil state is very uncertain and irregular. Sometimes it evidently fell to pieces when exposed between the rays, and no trace of it is found preserved; sometimes it was folded deeply inward between the rays, and so covered with matrix that it has not been observed in the fossils. This has often led to misconception of the real structure, and to misrepresentation of the facts in illustrations. For instance, it was at one time a matter of dispute whether the genus *Taxocrinus*, as then supposed to be represented by *T. tuberculatus* from Dudley, possessed any interbrachial connection between the rays, beyond a possible single plate. Proper cleaning now discloses, in many specimens of that species, the integument of small plates rising high up between the rays and their divisions. The characteristic appearance of this armlike series of anal plates, and also of the perisomic integument, is well shown in Wachsmuth and Springer's figures of *Taxocrinus intermedius*,[1] and also in the various figures of *Onychocrinus* herein (Plate IV).

Sometimes the rays lie so close together that they touch the anal series on both sides, and the bordering integument is thus folded inward so that it cannot be seen from the exterior. Nevertheless,

[1] *Proceedings*, Academy of Natural Science, Philadelphia, November, 1888, Plate XVIII.

the anal plates usually preserve their rounded appearance, and do not seem to form part of the calyx wall, or to be suturally connected with contiguous rays. Such cases as this give rise to difficulties of interpretation, because these are some forms in which the anal plates rise into a single vertical series connected by suture with the adjacent brachials, and flush with them. These must be distinguished from the cases just alluded to, where there is a rounded, armlike row of plates, so closely crowded by the rays that there is neither any part of the integument visible, nor any vacant space on either side, but which were evidently not joined to the brachials by suture. Both cases would answer the description "anals in a vertical series," and yet they undoubtedly represent the two distinct plans, which here, as elsewhere, run into perplexing transition forms.

The armlike row of plates, while not tubular, but on the contrary formed of thick and solid plates, is supposed to compose the dorsal support of an anal tube, formed by the outward growth of the perisome caused by the extrusion of the rectum. If we sometimes in descriptions call this row of plates "tube-plates," or the "anal tube," it must be understood as a conventional term—used by many former writers in this sense—to avoid circumlocution, and not as implying that the plates themselves are hollow, or strictly form the wall of a tube.

Now the position of this row of plates shows in a striking manner the effect of that strange influence which has modified the bilateral symmetry of almost every genus in this entire group. The small infrabasal is almost invariably located under the right posterior ray; the radianal originates under the right posterior ray; it migrates from this position upward until it disappears, but always to the right of the median line; if the arms have an asymmetrical distortion, it is to the right, never to the left. And so this vertical series of anal plates is affected by that tendency, which persists long after the radianal has disappeared. The posterior basal on which it rests is excavated into a sort of shallow socket, like the articulating facet of a radial, on the right shoulder of the plate, so that we will usually see a small tongue or angle of that plate rising up to the left of the base of the anal plate higher than to the right; or, if the socket-like excavation is not so plain as this, the upper edge of the basal is distinctly sloped to the right.

Not only so, but the anal series itself leans to the right, so that the vacant space, or the plated integument if it is preserved, is always widest at the left; and the anal plates are sometimes found firmly cemented by pressure to the side of the right posterior ray, leaving no other plates visible at that side, and giving an appearance of sutural union which must be guarded against in studying these fossils. The shape and position of this anal row of plates are subject to much variation, owing to pressure in fossilization, but the dextrorse asymmetry is almost the invariable rule. There does not seem to be in this form any special equivalent of the anal *x*. It would naturally be the lowest plate, resting on the posterior basal—the original plate of the *Antedon* larva, or of our supposed prototype—but it has been so encroached upon by the growth of perisome at the sides that it is relatively small, and the plates of the series show only a gradual taper from the proximal end upwards.

This plan of anal structure began in the Lower Silurian, and is found in the Taxocrinoid genera, with or without a radianal, from *Eutaxocrinus* and *Gnorimocrinus* in the Silurian, to *Taxocrinus* and *Onychocrinus* in the Carboniferous, surviving until the Kaskaskia, long after the other plan was extinguished. Being thus so characteristic of that line of genera, it may well be called the Taxocrinus plan. It has persisted to the present time, being found in a very characteristic form in *Thaumatocrinus* (Plate IV, Fig. 6).

2. The second plan is that of a simple extension of the anal system by the addition of other plates of similar solid nature to that of the original plate, and which are joined by sutural union to the adjacent plates of the posterior rays, and also with each other; so that, as far as they extend upward, they are incorporated into the calyx walls in the same manner as the plates of the other interbrachial areas. The posterior basal is either simply truncate, followed by one plate; angular, followed by two plates; or truncate with sloping shoulders, followed by three plates; but in each of these cases all the plates, and others of a similar nature succeeding them, form by sutural union (of course of the loose order characteristic of the whole group) part of the calyx wall.

This form of anal structure is found from the Silurian to the Carboniferous. The primitive stage of it is found in such genera as

Lecanocrinus (Plate VI, Fig. 13), and *Anisocrinus* (Plate VI, Fig. 10), in which the posterior rays arch over the anal plate, leaving no vacant space above it. In *Calpiocrinus* we see its simplest extension by the addition of single plates in succession above it (Plate VII, Fig. 7). In *Temnocrinus* we have a further modification by the addition of two or three plates abutting on the anal (Plate VII, Fig. 15). The development was rapid, for in another Silurian genus, *Sagenocrinus*, in which the dextrorse asymmetry caused by the presence of a radianal is still a feature, we have a perfect example of this plan in its fullest extension, where the anal area, following upon an angular posterior basal, is completely filled to the height of several orders of brachials, with solid plates, forming a regular continuation of the calyx wall. Because of its remarkable development in that genus, this form of anal structure may appropriately be called the Sagenocrinus plan. It is carried forward with equal perfection into the Carboniferous by the genus *Forbesiocrinus*. in which the radianal has been eliminated; and it ends in the Keokuk and Warsaw with species in which the asymmetry of *Taxocrinus* forms without a radianal has nearly disappeared, and the bilateral symmetry of the calyx is almost perfect. In most cases, however, asymmetry may be seen in the longer slope of the right shoulder of the posterior basal (Plate VII, Fig. 20). Where the posterior basal is truncate, the succeeding plate may be taken as the anal *x*, but where it is angular, as is most frequently the case, the anal *x* is apparently split in two, giving rise to two or more series of other plates above. While there are thus a few cases, as indeed we find also in the Silurian in forms like *Calpiocrinus*, which seem to be bilaterally symmetric, yet it is a fact that the dextrorse aysmmetry remains also as a general characteristic of this form as well as the Taxocrinus form. If the posterior basal is angular above, the right sloping face is generally the longest, and the series of plates following it a little the largest; if it is truncate and followed by one large plate which is angular above, the same remark may apply to the second plate; if it is truncate with sloping shoulders, the series from the right shoulder usually seems a little the stronger, and rises higher along the ray than the others.

Between such genera as *Calpiocrinus*, *Temnocrinus*, and *Sagenocrinus* there are considerable variations of this plan; but throughout

its entire range—except in certain peculiar transition cases to which I will allude later—there is no suggestion, in the external form, of any such structure as an anal tube.

Under this form, as well as the first, the modification reached the phase of the entire disappearance of the anal plates, first in the Silurian without disturbing the radianal, as in *Ichthyocrinus*, and afterwards in the Carboniferous with complete elimination of that plate, as in *Metichthyocrinus*.

Looking at these well-marked examples of the two plans, one cannot fail to be impressed with their complete distinctness as they stand side by side in the Silurian (Plate VII, Figs. 16 and 18), and in the Carboniferous (Plate VII, Figs. 17 and 20). They run a somewhat parallel course during the greater part of the paleontological history of the group, but not to the end. The Sagenocrinus plan ceases with the genus *Forbesiocrinus* in the upper part of the Keokuk or Warsaw Limestone, while the Taxocrinus plan survives to the last in the genera *Taxocrinus* and *Onychocrinus*. The latter is thus the one character connected with the anal structures which survived from the Lower Silurian to the extinction of the group in the higher Carboniferous, and is continued to the present time in one genus of the Flexibilia Pinnata. Only one specimen belonging to the Flexibilia Impinnata is known from rocks later than the Kaskaskia, and that is an Ichthyocrinoid from the Lower Coal Measures, of which the calyx is unfortunately wanting. When its characters are made known by future discoveries, I shall expect to find it with an anal side of the Taxocrinus type.

Notwithstanding the evident distinctness of the two plans, their early divergence from a common origin which can with reasonable probability be inferred, and their long duration as independent lines of structure, it is nevertheless a curious fact that they also tend to run together, in a sort of convergent evolution, toward the close of their history. I can show most beautifully by actual specimens how this has occurred in the Carboniferous between *Forbesiocrinus* and *Taxocrinus*, not so much in the way of individual variations as in the modification of species. We have a species of *Forbesiocrinus* in the Keokuk Limestone with a firmly plated anal area, in which there is a well-marked vertical series imbedded in the middle, but usually

tending toward the right. On the other hand, there is in the same formation, and at apparently the same horizon, a form of *Taxocrinus* in which, while the anal series is rounded and prominent, and merges plainly into the perisome above, the plates of the bordering integument, though still pliant, are strong and heavy, and apparently united to the adjacent brachials by loose suture. In these the modification begun in the last case has evidently been carried to a phase in which the strong structures composing the *Forbesiocrinus* plan have broken down in the anal area, and given place to the opposite one. It thus happens that we are sometimes in doubt to which of the two genera a species ought to be referred; and much of the confusion and shifting of opinion as to the relations of these genera is traceable to the failure to take proper account of these transition forms.

There was thus a sort of struggle for existence between the two plans, and it would seem that the group adhered in the end to that structure which was in best accord with its flexible characteristics; and we may perhaps infer that the Sagenocrinus plan, which tended more in the direction of the Camerate structure, was finally extinguished by reversion to the other one. This was fully accomplished in the Kaskaskia, where there is a species described by Hall as *Forbesiocrinus whitfieldi*,[1] and better illustrated by Miller and Gurley under the name *Taxocrinus wetherbyi;*[2] and of which Wetherby's *Forbesiocrinus parvus*[3] is a young individual—which has the habitus of the highest-developed *Forbesiocrinus* in everything except the anal side, where it is a perfect example of structure No. 1. In fact, the general character of the *Taxocrini* in the St. Louis and Kaskaskia Limestones is that of a strong interbrachial structure in the regular areas, combined with a weak and flexible one in the anal area, containing the conspicuous tube and its bordering integument.

In the first family—Ichthyocrinidae—structure No. 2, in its earlier stages, was the prevailing type, viz., one large plate, with perhaps the addition of a few smaller ones above it, completely filling the area. *Parichthyocrinus* alone of the genera hitherto assigned to the Ichthyo-

[1] *Geological Survey of Iowa*, Part II, p. 632.

[2] *Bulletin No. 6*, Illinois State Museum, Plate 4, Fig. 3.

[3] *Journal of the Cincinnati Society of Natural History*, Vol. II, Plate II, Figs. 4*a*–*b*.

crinidae, has the Taxocrinus anal structure thoroughly developed. Only its habitus of closely abutting arms differentiates it from *Taxocrinus*, and it must therefore be considered simply as a somewhat abrupt transition form from the Taxocrinidae toward the Ichthyocrinidae, or *vice versa*. But it is most interesting to note that in certain forms referred to *Lecanocrinus* we can almost see the transition actually going on, in the same horizon and locality. In *L. macropetalus*, from the Niagara group at Lockport, N. Y., we have a most characteristic example of the first family—a rounded, ovoid crown, with a perfectly even surface, with rays and arms flat dorsally and in close contact throughout (Plate VI, Figs. 13, 14). It has a single very large anal plate rising above the level of the radials, and curving to a point between the rays, which abut upon it at either side and close over it in an arch. This plate is without depressions of any kind, and is perfectly flush with the general curvature of the crown. In certain other species from the same locality and horizon, this plate begins to be depressed at the sides from the upper end down, so as to leave a ridgelike elevation in the middle, quite resembling the base of our so-called anal tube, while the full dimensions of the plate are still retained. In some specimens of these forms we can see this median ridge continued by a second small rounded plate, of the same form and size, the large anal having lost its pointed angle and become truncate to support this new plate. Here we have the beginning of our armlike anal series. If the process is pushed a little further, so that the depressed lateral margins of the large anal plate become replaced by perisome, we shall have a complete Taxocrinus anal side, and our *Lecanocrinus* will have been transformed into a *Gnorimocrinus*. It is now very curious that the tendency is actually in this direction as to those other characters on which the two families have been separated; for along with these changes in the anal plate there appear marked depressions between the rays and their divisions, which become rounded, with strong tendency to divergence in the upper portions, and to long and delicate arms. Hall's *Lecanocrinus ornatus*,[1] and Ringueberg's *L. nitidus*, *L. incisus*, and *L. excavatus*,[2] are forms in which this interesting modification occurs. I have de-

[1] *Palæontology of New York*, Vol II, Plate 44, Figs. *2a–m*.

[2] *Bulletin*, Buffalo Society of Natural History, Vol. V, Plate 1, Figs. 5, 6, and 7.

scribed this as a modification from *Lecanocrinus* toward *Gnorimocrinus*. Of course, we do not know which way it really was, and it is quite possible that the process of modification was in the opposite direction.

Which of these two plans was the primitive one we cannot determine from their paleontological history, as they both doubtless run far back into the obscurity of pre-Silurian epochs. The earliest known species of undoubted Flexibilia type—*Taxocrinus elegans* and *T. laevis* from the Trenton Limestone—I believe to have the Taxocrinus anal side;[1] and, on the other hand, *Cleiocrinus*, from the same horizon, which is at least a transition form with some flexible characteristics, has the opposite anal plan. There is, however, to be considered the question whether the morphological differences which gave rise to this structure have not continued to the present time in the Flexibilia Pinnata; and we may, in that connection, venture an opinion as to their probable origin.

The modifications in the external form of the calyx were undoubtedly due to differences in the position of the anus. If the gut issued from the visceral mass laterally, and remained there, the growing skeleton would be affected by its position, even to the extent of simulating its outline; and the lower down it issued, the more pronounced would be the separation of the rays by the tubelike structure. If it issued ventrally, and from the center of the disk, the skeleton would not be influenced by it at all, but should have perfect pentamerous symmetry. Between these two extremes we should have a wide range of variation in the outward form and arrangement of the anal side. And we may suppose that, as it shifted from a very low, lateral position, toward the margin of the disk, the tubelike row of plates would gradually disappear, or lose its identity by becoming incorporated in plates suturally united to the rays, like those of the regular interbrachial areas. By the time it had shifted well into the central part of the disk, all anal plates would be eliminated from the skeleton. Or the shifting might have taken place in the opposite direction, and the order of the changes in the skeleton have been reversed accordingly; although the first is more in accordance with

[1] This supposition is confirmed by the discovery of specimens since the above was written.

the observed facts. Such shifting in the position of the rectum is a fact well known in the embryology of the Echinoderms;[1] and it may be remarked that there are instances, both among the Camerata and the Inadunata, where the anus passed out through the test below the level of the arm-bases.

Fortunately for the purpose of our comparison, the only Crinoid whose embryology we know belongs to the Flexibilia. It has been the subject of elaborate and splendid researches by several distinguished and able investigators. The course of development of the anal plate in the larva of *Antedon*, as brought out by the works of these eminent men, lends force to the above suggestion.

Sir Wyville Thomson's account[2] of it is as follows:

> About the period of the development of the second radials, a forked spicule makes its appearance in one of the interradial spaces between the upper portion of two of the first brachial plates. This gradually extends in the usual way till it becomes developed into a round, cribriform, superficial plate. Simultaneously with the appearance of this "anal" plate, a cæcal process like the finger of a glove rises from one side of the stomach and curves toward the plate. The plate increases in size, becomes inclosed in a little flattened tubercle of sarcode, and maintaining its upright position it passes slightly outwards, leaving a space on the edge of the disk between itself and the base of the oral plate immediately within it. Toward this space the cæcal intestinal process directs itself. It rises up through it in the form of an elongated tubular closed papilla. The summit of the papilla is finally absorbed, and a patent anal opening is formed.

Dr. W. B. Carpenter continued the researches begun by Sir Wyville upon the development of *Antedon rosaceus*, and he has given,[3] with most admirable illustrations, the complete history of the anal plate. For the convenience of readers who may not happen to have this work at hand, I reproduce a few of his figures—some on a different scale of enlargement—which will assist me in explaining the thought I have in mind. In quoting some parts of Carpenter's description, I refer to the figures on my own plate instead of to his original numbers. He gives the following statement of the first appearance and subsequent history of this plate (p. 727):

[1] Bury on "Early Stages in the Development of *Antedon rosacea*," *Philosophical Transactions*, 1888 B, p. 294.

[2] "On the Embryology of *Antedon rosaceus*," *Philosophical Transactions*, 1865, p. 529.

[3] *Philosophical Transactions*, 1866, pp. 671 ff.

Between two of the radials, and at the same level with them, an unsymmetrical plate early shows itself, the subsequent relation of which to the vent proves it to be an *anal* plate (Plate V, Fig. 4). . . . . Simultaneously with the appearance of the anal plate, a slender digitate process arises from one side of the stomach, and curves toward that plate: this constitutes the rudiment of the Intestine.

This is at a very early stage. At a little more advanced stage, shown by Figs. 5 and 6, Plate V, the account proceeds:

The single anal plate originally interposed between two of the first radials (R. R.), being attached not so much to the neighboring plates as to the visceral mass, begins to be lifted out (as it were) from between them with the development of the anal funnel; and the space left by it is partly filled up by the lateral extension of the two radials between which it was previously interposed, but which do not yet come into complete contact (p. 732).

At a still later stage:

The anal funnel (Plate V, Fig. 6) is now a very conspicuous object, the anal plate (*x*) which it bears on its outer side being altogether lifted out from between the two first radials which it originally separated (p. 734).

The anal plate finally disappears altogether before the adult stage is reached, and the anus takes up its permanent position toward the margin of the disk.

Thus we see that the position and movements of the anal plate are not governed by its connection with other plates of the aboral side, but that they depend upon the shifting and development of the gut, to which it is at an early stage attached. And we can readily trace, in the movements of the plate thus indicated, striking analogies to some of the anal conditions observed among the paleozoic genera.

Now we have, in the two great living genera of the Flexibilia Pinnata, just such differences in the position of the anus—though in less degree—as we have supposed to occur among the ancient forms; viz., that of *Antedon* being excentric, while that of *Actinometra*, alone of all known living Crinoids, is absolutely central. The excentricity of *Antedon*, while producing an anal plate in the larval skeleton, is not sufficient, or sufficiently persistent, to affect the form of the calyx in the adult, which in both genera has perfect pentamerous symmetry. It may be, therefore, that we have in these living genera a reminiscence of the long struggle among their paleozoic antecedents between these opposing tendencies.

We may also be warranted in supposing, from the observed course of development of the anal structures in the larva of *Antedon* as above described, that the Taxocrinus plan represents the earliest and most primitive form, and that the modifications of this in paleontological time were those which tended toward the disappearance of the row of anal plates, with its border of perisome, and the substitution of regular calyx plates, suturally connected with the adjacent rays. Hence the outcome of the struggle in paleozoic time was the survival of the original plan, and the suppression of the modified one.

3. The third modification of the anal structures, which also runs from the Silurian to the Carboniferous, is that in which the anal plate has altogether disappeared, and it is merely a further extension of one of the preceding. This occurred in the Silurian in the genus *Ichthyocrinus*, while still retaining its primitive radianal, which it did not get rid of until the Carboniferous, where, in the genus *Metichthyocrinus*, we have a Crinoid with perfect pentamerous symmetry, so far as the external test shows. Two genera in the division with divergent arms reach this stage also in the Carboniferous—*Wachsmuthicrinus*, in which traces of bilateral symmetry can be seen in the slightly larger size of the posterior basal, and *Nipterocrinus*, in which the pentamerous symmetry seems to be perfect. This modification apparently did not much influence the history of the group.

c) The first modification in the brachial system—i. e., in the number of primibrachs—has already been described and discussed as to its details. There can be little question that the primitive form in this respect was that with two primibrachs. It belongs to the *Antedon* larva, and it prevailed almost exclusively in the Silurian. The few cases in which there is but one primibrach may be explained by the syzygial union of two of the primitive brachials, just as happens in some species of the living *Antedon*, without changing the fundamental plan. The addition of another primary brachial simultaneously in all of the rays, producing the 3-IBr structure, cannot be explained in any such way, and the occurrence of this form in the Silurian is so limited and exceptional that it may scarcely be said to have had a beginning before the Devonian. It is clearly the successor of the first one, in the paleozoic. The two-IBr structure con-

tinued from the Silurian through the Devonian, and into the Carboniferous, with constantly diminishing importance, ending, so far as known, in the Keokuk Limestone; but reappearing with the Flexibilia Pinnata in the Mesozoic, and continuing to the present time. The three-IBr structure, on the other hand, having barely made a beginning in the Silurian, shows a steady increase through the Devonian and Carboniferous, and prevailed exclusively in the Warsaw, St. Louis, and Kaskaskia, in the genera *Forbesiocrinus*, *Taxocrinus*, and *Onychocrinus*, with a slight tendency in *Taxocrinus* of the Kaskaskia, to reversion to the original form. Therefore this is not a case of parallel development, but is that of the suppression of the earlier structure, and its replacement by the later one, which disappeared only with the extinction of the nonpinnulate division of the Flexibilia toward the close of the Carboniferous. In the latest and most extravagant genus of the group, *Onychocrinus*, it shows a tendency to further development by the addition of another brachial, not sporadically, but constantly, as a well-defined character among species. From the tenacious grip that this structure had upon several of the strongest genera, it must be regarded as a morphological change of much importance, strongly affecting the phylogenetic history of the group; but yet subordinate, in my opinion, to the great differentiation of the anal structure, and therefore not available for defining large divisions.

The second brachial modification is marked by interesting changes in the mode of branching of the rays above the first axillary from a more or less regular division of the rays by successive bifurcations—dichotomy—to one into large main branches, or arm-trunks, bearing ramules on one or both sides—heterotomy. Both were established in the Silurian, and continued through the Devonian and Carboniferous, and were in force, side by side, in the genera *Taxocrinus* and *Onychocrinus*, at the close of the Subcarboniferous in the Kaskaskia. The dichotomous plan, which was probably the primitive one, was by far the most prevalent throughout; and the heterotomous plan was a modification which, while it ran parallel to the other until the end of the group, did not supplant it. The differences arising out of this modification afford very good characters for generic distinction.

d) The modification in the plates of the interbrachial areas might properly have been considered in connection with those of the anal side, inasmuch as they all belong to the system of supplementary plates, as distinguished from that to which the brachials belong. Sir Wyville Thomson was led by his researches on the embryology of *Antedon*[1] to regard the skeleton of the Crinoid as composed of two systems of plates, which he states to be thoroughly distinct in their structure and mode of growth. These he designated as the *Radial*, and the *Perisomatic*, systems of plates. The former are distinguished by being chiefly made up of peculiar fasciculated tissue of parallel rods, while the latter commence as simple cribriform films embedded in the outer layer of the perisome, and thicken by a repetition inwards of the same diffuse areolar tissue. The Radial system he considers to include the joints of the stem, the centrodorsal plate, the radial plates, and the plates of the arms and pinnules, or brachials. To the Perisomatic system he refers the basal and oral plates, the anal plate, the interradial plates sometimes seen between the second radials, and any other plates or spicules that may be developed in the perisome of the cup or disk. Dr. Carpenter,[2] while not agreeing altogether with Sir Wyville as to the grounds of differentiation of these plates, substantially recognizes the two systems of radial and perisomatic plates as defined by him, except that he ranks the basal plates with the former instead of the latter.

Wachsmuth and Springer[3] divided the plates of the Crinoid skeleton into *primary* and *supplementary* plates; the former including the stem joints, infrabasals, basals, radials, brachials, orals, and ambulacrals, and the latter the anal, interbrachial, and interambulacral plates. According to either of these groupings of the plates, the anals and interbrachials fall under the same category. It was also demonstrated by Wachsmuth and Springer[4] that all plates interposed between the rays, from the basals to the orals, whether interbrachial or interambulacral, belong morphologically to the same ele-

[1] *Philosophical Transactions*, 1865, p. 540.

[2] *Ibid.*, 1866, p. 742.

[3] *North American Crinoidea Camerata*, pp. 38–105.

[4] "The Perisomic Plates of the Crinoids," *Proceedings*, Academy of Science, Philadelphia, 1892, pp. 345–75.

ment. Hence it follows that, if in the growing Crinoid certain spicules of the ventral perisome developed into well-defined plates, which remained permanently in a definite position in the axils between the radials or brachials, they would become the interbrachial (or interradial) plates as we know them; so that whether a certain form has interbrachials or not depends upon the extent to which the perisome developed downward into the axils.

Some traces of the development of this element are to be found in the *Antedon* larva. Sir Wyvill Thomson[1] thus describes their occurrence:

> In one or two cases I have observed about the time of the first appearance of the anal plate a series of five minute rounded plates, developed interradially between the lower edges of the oral plates and the upper edges of the basals. These interradial plates sometimes remain permanent in the mature *Antedon rosaceus*, and they appear to be constantly present in some species, as for instance in another and rarer British form, *A. milleri*. They usually occur, finally, in groups of three or five. They are irregular in form, and they resemble the anal plate in structure and mode of growth.

Dr. Carpenter figures two clusters of these plates, as seen at the inside of the calyx;[2] and J. S. Miller shows one such plate in each axil of his *Comatula fimbriata*,[3] which he calls "intercostal plates or joints." These observations of the so-called interradial plates in *Antedon* have been rather discredited by some subsequent authors in the course of controversial discussions, but I see no reason for questioning them. The occurrences as described seem to me entirely in harmony with the morphology of the group, and if they had not already been seen, I should confidently expect them to be found by further research.

It is evident from Dr. Carpenter's figure that these plates are more conspicuous on the interior of the young *Antedon* than at the exterior; in other words, that the growth is from within outwards. This accords very well with the observed facts among the fossils of this group. I have many specimens showing how the interbrachial plates diminish in size and number from the interior of the calyx to the exterior. In many cases where they are well developed on the

[1] *Op. cit.*, p. 540.

[2] *Philosophical Transactions*, 1866, Plate 39, Fig. 7.

[3] *Natural History of the Crinoidea*, Frontispiece, Fig. 2, G.

inside they appear as mere points at the outer surface, and often they do not pass through the wall; so that in a given interradius we may count twice as many plates interiorly as exteriorly. In some genera which are usually without any such plates, a straggling one is occasionally seen, and it is quite probable that, if we could see the interior of all the specimens, we should find many instances of such plates which have not come to the surface. It is a fact thoroughly established that these plates multiply with the growth of the individual; but it would seem that in those forms in which the rays are more or less contiguous, and tend to arch over the interbrachial areas, the plates are crowded by the growth of brachials, and to a certain extent reduced or suppressed at the outer surface of the calyx. In genera like *Taxocrinus*, *Forbesiocrinus*, and *Uintacrinus* the variance of the interbrachials with age is very marked, young individuals in some species having none at all, while the adults are profusely supplied. In *Wachsmuthicrinus*, which has no anal plate, the interbrachials are still more variable, being present or absent in the adult of the same species. In *Nipterocrinus*, and probably in *Pycnosaccus*, and the form described by Angelin as *Forbesiocrinus obesus*, the perisome extended down to the radials as a plated integument, without developing any well-defined interbrachial plates.

Notwithstanding the irregularities in some cases above mentioned, the varying development of the interbrachial plates affords important characters for classification in this group. In some genera the perisome did not extend down between the rays in such a manner as to form any permanent plates in the interbrachial areas; in others they were abundantly developed. Both forms extend from the Silurian to the Carboniferous; the first being characteristic of a little group of genera which may be taken as the typical Ichthyocrinidae, and correlating with another character to be mentioned presently. The tendency in the paleontological history of the group generally is the same as in the individual, viz., toward an increase in interbrachials. But few forms without such plates are found after the Silurian, while in the Carboniferous their presence in considerable numbers is the general rule. Nevertheless, the latter stage was fully attained in the Silurian in the genus *Sagenocrinus*.

There is another modification, not suggested by anything apparent in the primitive type, but affecting the general form and habitus of these Crinoids in a way that is of considerable practical importance. Anyone who has had occasion to arrange the fossils of this group cannot help being struck by the presence of two general types. One is marked by a tendency of the calyx and arms to form a globose, ovoid, or pyriform crown, in which the arms lie in close contact—although in some genera the lower part of the rays are separated by wide interbrachial areas, above which they come together again. In the other, on the contrary, the tendency is toward a spreading crown, caused by the increasing divergence of the rays upward. In the first the plates of the rays and arms, and the intervening interbrachial structures when present, are for a considerable distance up more or less flush with one another exteriorly, so that the general curvature of the crown is but little interrupted. In the second, the rays and their divisions are rounded exteriorly, and the interbrachial spaces relatively depressed, so as to emphasize the appearance of divergence above alluded to.

Between such forms as *Ichthyocrinus* or *Lecanocrinus* on the one hand, and *Taxocrinus* or *Onychocrinus* on the other, there is not the slightest difficulty in distinguishing by the above character. But there are occasional species, otherwise characteristic of the first group which are pretty deeply furrowed between the rays and arms, and some of the second whose arms are habitually rather closely packed together, which we could not so readily assign to their respective groups, except for their evident connection with related genera whose characteristic species fall within them without any trouble. On the other hand, there are a few forms which we are inclined to transfer from the group which they superficially resemble, because of some peculiar association of other characters which indicate a probable closer relationship elsewhere.

Now, I confess myself unable to point out any satisfactory morphological basis for the difference in habitus between these two divisions, and I have much doubt as to its structural importance. Yet it is so constant and well marked in many cases, and affords such a palpable and convenient means of separation in this perplexing group, that we find it of some use in our classifications. It formed

a rather too prominent basis of my former arrangement. Both forms existed in the Lower Silurian, and continued into the Carboniferous; the first one greatly diminished and ending in the Keokuk Limestone, with a single exception—probably a transition form—in the Coal Measures; and the second continuing with increasing importance to the end of the Subcarboniferous. The first division comprises a little group of rare genera, mostly confined to the Silurian, but with evident descendants in the Devonian and Carboniferous. They are mostly small, *Ichthyocrinus* alone occasionally attaining a considerable size. In the number of primibrachs and the absence of interbrachials they fall together nicely, and in the structure of the anal side they represent, for the most part, an earlier stage of development of the *Sagenocrinus* plan than those of the other division. The second division, with the divergent arms, embraces genera of both forms of brachial modification, and also the two leading types of anal structure. It appeared in the Silurian, and steadily increased to the close of the Kaskaskia, where it is represented by its most conspicuous example, *Onychocrinus*.

It is evident that most of the modifications above considered have influenced the line of succession from the primitive type of this group, and its separation into subordinate divisions. Each one of them is doubtless a factor entering into the classification that nature has made—though of very different values—and the probability is that every natural division which has been produced is a composite product, the resultant of the interaction of two or more of these tendencies to modification upon independent lines. Just how much influence each has had in fixing the line of succession we have no means of determining. It is possible to arrange the genera upon the basis of either one of the leading morphological changes I have mentioned; but whichever is selected for this purpose, we find our arrangement more or less disturbed by some of the others. For example, a fairly satisfactory arrangement could be based upon the modification of the primary brachials, which would correlate quite well with other characters, if it were not for the fact that this would throw *Sagenocrinus* and *Forbesiocrinus* into different families; whereas the connection betewen these genera is so evident, and the line of descent

so probable, that we cannot feel like accepting any scheme which compels their separation. We cannot, of course, represent lines of descent in space of two dimensions, so that anything in the way of a diagram or table would be imperfect, even if we knew all the facts. Still less is it practicable when many of the relationships rest wholly in conjecture.

In some groups of the Crinoids family divisions are most sharply marked. No one need ever be in doubt, from inspection of the calyx alone, whether a Camerate Crinoid belongs to the Rhodocrinidae, Melocrinidae, Actinocrinidae, Batocrinidae, Platycrinidae, or Hexacrinidae. This cannot be said of the Flexibilia. By reason of the fundamental difference in construction of the two groups, there is not in the latter that sharp demarkation between calyx and arms which is so characteristic of most of the Camerata. Here, on the contrary, in by far the greater number of the genera, the calyx passes into the arms by imperceptible gradation, so that in the fossil state, being usually unable to see any part of the tegmen, we cannot tell with certainty where the calyx ends and the arms begin. The different modifications of this structure also shade into one another by various transitions, which is the reason why groups of family rank may be formed, as above stated, which differ somewhat according to the character which is taken as the basis of division.

Nevertheless, it seems possible to form a reasonable opinion as to the relative importance of the characters, as the basis for large divisions:

1. The differentiation of the anal area, being found completely developed in the earliest Silurian, and continuous almost to the end of its history, may be taken as marking the most primitive division of the group. It evidently dominated the lines of descent throughout, and should therefore be accorded first importance in the definition of families, all others being subordinate modifications, affecting one or the other of these lines, but probably not interrupting them.

2. The presence or absence of interbrachials affords a useful basis of subordinate divisions.

3. The differentiation of the brachial system in the number of primary brachials, although evidently affording characters of much importance, is one which has impressed itself with varying force

upon the two primitive lines, and not in a parallel progression. It may be assumed to be a subordinate modification, marking the limitations of genera, and perhaps of sub-family divisions.

4. The difference in general form and habitus, while not explainable upon any known morphological ground, and therefore with our present knowledge apparently of less value than either of the foregoing, nevertheless furnishes a ground for division which is of some practical importance in the construction of a table, and it may therefore be given a rank in our classification perhaps higher than it at present logically deserves.

The other modifications are so palpably limited in their effect upon the history of the group that they need not be considered except in the separation of genera. I do not believe that the higher arm structure is a good character for the definition of families. It appears in parallel successions in other groups of the Crinoids, where it is most interesting in the development from more or less equal branching to radial extensions in the form of main arm-trunks or branches bearing subordinate ramules. This is conspicuously shown among the Camerata in several of the best defined families, viz., in the Rhodocrinidae from *Rhodocrinus* to *Ripidocrinus;* in the Melocrinidae from *Glyptocrinus* to *Melocrinus;* in the Actinocrinidae from *Actinocrinus* to *Steganocrinus;* in the Platycrinidae from *Platycrinus* to *Eucladocrinus;* and in the Hexacrinidae from *Arthracantha* to *Hexacrinus*. Yet there can be no thought of questioning the arrangement of these beautifully defined families on account of these arm characters, or of contending that they represent anything more than a minor variation.

The arrangement of which I am at present in search is one for practical utility, that will facilitate the study of this group; and I am not attempting to express fully the phylogenetic relations of the various forms even as I might conceive them to be, although I have tried to recognize some of the evident lines of descent. Taking as a basis the primitive differentiation of the anal system, the Flexibilia Impinnata may be divided into two groups, and the first of these may be again divided upon the interbrachial system and the general form and habitus. This will give three main divisions, A, B, and C; of which A and B will agree with each other and differ from C in

the anal structure, while they will differ from each other in the interbrachials, and partly in the form. In this way the known genera of this group—with the exception of some transition forms whose place is difficult to assign—will fall into three principal family divisions, which differ from each other in various degrees, according as one or the other character is given the greater importance. Each of them contains further groupings of genera upon some of the other characters, which might be given subordinate designations according to our notions of their value.

This might be considered an imperfect attempt to work out the resultant of the several modifications which I have mentioned, and it necessarily encounters difficulties which can be evaded only by some arbitrary—and perhaps temporary—disposition of the disturbing elements. As to these no scheme will ever be perfectly satisfactory, and there will always be some shifting of opinion by different observers, and even by the same observer from different points of view. For instance, as to some of the characters, we cannot always give them the same order of precedence in the tables. If we had genera showing every possible combination of the modifications we have discussed, it might be practicable to construct a table with some uniform order of sequence. We do not, however, find all such combinations, and it is quite conceivable that they were never all accomplished. But it is also to be confidently expected that some additional ones will yet come to light, and we can readily point out some vacancies to be filled by future discoveries.

These three families are not so very different from those heretofore proposed, although the grounds upon which they are defined are considerably changed. In my former paper, above cited, I arranged the genera into two main family groups, based upon the difference in the habitus and general form; and I stated that the second family might perhaps be divided into two subgroups. There is no very material difference in the general arangement I now propose, except that I carry this suggestion a step farther, and erect the two subgroups into families of equal rank with the first, thus bringing in an additional family—Sagenocrinidae—between the other two; while also restricting the first group within somewhat narrower limits.

The definitions of a number of the genera differ considerably

from those given by Wachsmuth and Springer in the *Revision of the Palaeocrinidae*, Part I. Discovery and research since that time have greatly added to our information touching this group, which was then by no means well understood. In *Gnorimocrinus* the typical species is *G. expansus* Ang.,[1] and several of the species listed under this genus in the *Revision* are now found to belong to other genera. For instance, *G. excavatus* Schultze doubtless belongs to *Dactylocrinus;* and perhaps *G. oblongatus* and *G. rigens* also. *G. ovalis, salteri, interbrachiatus*, and *austini* I have referred to a new genus, *Protaxocrinus;* while *G. loveni*, by reason of its possession of three primibrachs, and a radianal in addition under the right posterior ray, will form the type of another new genus, for which I propose the name *Meristocrinus*.

In *Lithocrinus* the typical species is *L. divaricatus* Ang. (including *L. robustus* syn),[2] which has no radianal; while for *L. obesus*, which has a radianal, and apparently a different interbrachial structure, I have found it necessary to propose a new genus, *Cholocrinus*.

Under *Onychocrinus* there are two well-marked types, represented by *O. ramulosus* and *O. exsculptus*, which probably might be separated generically. The first has three primibrachs, and the latter four; and besides this, the habitus of the two species is so distinct that they can be recognized from the smallest fragments. The *exsculptus* type runs from the Burlington to the St. Louis, and probably to the Kaskaskia, and the *ramulosus* type from the Keokuk to the Kaskaskia.

In like manner, I think it probable that *Forbesiocrinus agassizi* with its two primibrachs, should be separated from the other species of the genus, which all have three. In fact, the analysis of the genera indicates the definition of other new genera which will have to be proposed, in order to cover cases already known or hereafter to be discovered.

The analysis of the Flexibilia genera here given is an improvement upon the former one, resulting from the foregoing observations. In considering any such arrangement, reasonable latitude must be allowed in construing descriptive terms, which cannot be made to fit all cases by any hard and fast lines. It must not be forgotten

[1] *Iconographia Crinoideorum*, Plate XX, Figs. 15, 16.

[2] *Ibid.*, Plate XXI, Figs. 11, 12, 21.

that the most important characters often shade into one another to a greater or less degree. For instance, in speaking of the arm-branching, we cannot confine the term "dichotomous" to such symmetrically dividing rays as are found in *Cyathocrinus;* but it must be taken to mean simply that the rays divide by a more or less regular bifurcation, as opposed to those in which the branches are given off in the form of lateral ramules markedly smaller than the main trunk, as in *Onychocrinus,* which we call "heterotomous." So as to whether the arms are contiguous or divergent, the terms are relative and not absolute; and while, as in other characters, the extremes are well marked, the two plans of arm arrangement sometimes approach each other so closely that all we can say in some genera is that the tendency is in one direction rather than the other. In the matter of interbrachials, there are really two kinds of plates: the regular, strong plates that occur in the axils, and the small irregular plates or granules forming the pliant integument which extends from the tegmen, in varying degrees, and for varying distances, down between the rays and their divisions. When in the descriptions we speak of "IBr plates," we mean the former.

It must also be remembered that it is impossible in any such scheme to represent the exact degree of relationship of genera, even as we understand it to be. We necessarily grade our divisions according to the greater or less generality of the characters; and we find in some cases that this will throw into different larger groups two genera that we should upon other grounds place next to each other.

Bearing in mind these qualifications, the following analysis may be found fairly practical, according to our present knowledge:

ANALYSIS OF THE GENERA

I. Anal plates, when present, incorporated in calyx by sutural union with adjacent rays.

A. Rays in contact all around, or separated only at anal side; arms contiguous . . . . . ICHTHYOCRINIDAE

a. Radianal.

i. RA under r. post. R.

Primibrachs 2.

Arms dichotomous.

Anal *x* alone, or followed by others . . . . *Clidochirus*

No anals . . . . . *Ichthyocrinus*

Arms heterotomous . . . . . .

ii. RA rhomboidal, obliquely to left of r. post. R.
Primibrachs 2 (exceptionally I).
Arms dichotomous; IBr 2 or 1.
Anal *x* alone, or followed by others in series. . *Lecanocrinus* (Cyrtidocrinus)

b. No radianal.
Primibrachs 2.
Arms dichotomous.
Anal *x* with triangular plate above; arms with dextrorse twist . . . . . *Mespilocrinus*

c. No anal nor radianal.
Primibrachs 2.
Arms dichotomous . . . . . *Metichthyocrinus*
Primibrachs 3.
Arms dichotomous.
(Anal side unknown, but from form of calyx probably not distinct) . . . . . (*I. greenei*) . . . .

B. Rays separated all around by interbrachial plates SAGENOCRINIDAE

a. Radianal.
1. Anal area more or less completely filled by solid plates, forming part of calyx wall.
i. Large anal *x* alone, or followed by others in single series.
Arms more or less contiguous.
Primibrachs 2 or less.
RA more or less under r. post. R., above the line of BB; iBr few.
Arms dichotomous . . . . . *Anisocrinus*
Arms heterotomous . . . . . .
RA variable, either between BB or absent.
Infrabasals very large, enveloping BB.
Arms dichotomous with ramules inside dichotom; iBr few.
10 main arm-trunks; RA generally present . . . . . *Homalocrinus*
20 main arm-trunks; RA generally absent . . . . . *Calpiocrinus*
Arms more or less divergent.
RA rhomboidal, obliquely to left of r. post. R.
Arms dichotomous; IBr generally 1.
iBr areas wide, occupied by small, irregular plates; IBr not filling distal face of RR *Pycnosacus*
Arms heterotomous; 10 main arm-trunks with ramules inside dichotom; iBr areas wide; IBr not filling distal face of RR.
(L. obesus n. g.) *Cholocrinus*

ii. Anals numerous, in more than one series.
Arms more or less divergent.
Primibachs 2.
RA more or less between BB.
Arms dichotomous; iBr numerous . *Sagenocrinus*

2. Anal *x* and smaller plates occupying only lower part of anal area.
i. Anals in more than one series.
Arms more or less divergent.
Primibrachs 2.
RA under r. post. R., above line of BB.
Arm dichotomous; iBr few . . . *Temnocrinus*

b. No radianal.
1. Anal *x* and smaller plates occupying lower part of anal area.
i. Anals few, mostly confined to single series.
Arms more or less divergent.
Primibrachs 2.
Arms dichotomous.
IBr areas wide; IBr not filling distal face of RR . . . . . .
Arms heterotomous.
10 main arm-trunks with ramules inside dichotom; IBr few . . . . *Dactylocrinus*
Arms more or less contiguous.
Primibrachs 2.
Arms dichotomous; iBr numerous (n. g.) *Amphicrinus*
Primibrachs 3.
Arms dichotomous; iBr few . . . *Euryocrinus*

2. Anal area filled by solid plates, forming part of calyx wall.
Anals numerous, in more than one series.
Arms more or less divergent.
Primibrachs 3 (exceptionally 2).
Arms heterotomous.
10 main arm-trunks with ramules inside dichotom.
iBr numerous . . . . . *Lithocrinus*
Arms dichotomous
iBr numerous . . . . . *Forbesiocrinus*

c. No anals nor radianal.
Arms more or less divergent.
Arms heterotomous. Primibrachs, 2.
10 main arm-trunks with ramules inside dichotom

iBr variable or absent . *Wachsmuthicrinus*
Arms dichotomous; Primibrachs 3.
iBr areas wide; IBr not filling distal face of RR., and connected by integument of small plates.
IBB undivided . . . . . *Nipterocrinus*

II. Anal plates, when present, not united by suture with adjacent rays, but in armlike series, more or less separated from them by perisome.
C. Arms generally divergent. . . . . TAXOCRINIDAE
a. Radianal.
i. RA under r. post. R.
Arms dichotomous; iBr few (*T. ovalis*, n.g.) *Protaxocrinus*
ii. RA obliquely to left of r. post. R.
Arms dichotomous; iBr few.
Primibrachs 2 . . . . . *Gnorimocrinus*
Primibrachs 3 . . . (*T. loveni*, n. g.) *Meristocrinus*
b. No radianal.
i. Arms dichotomous; iBr variable.
Primibrachs 2 . . . (*T. affinis*, n. g.) *Eutaxocrinus*
Primibrachs 3 . . . . . *Taxocrinus*
Arms contiguous . . . . . *Parichthyocrinus*
ii. Arms heterotomous; iBr variable.
20 main arm-trunks with ramules inside dichotom;
Primibrachs 2 . . . . . *Synerocrinus*
10 main arm-trunks, with ramules.
Ramules unilateral, outside of dichotom;
Primibrachs 3 . . . . . *Oligocrinus*
Ramules bilateral, branching in clusters on both sides of dichotom; Primibrachs 3 or more.
Onychocrinus
c. No anals nor radianal.

INTERMEDIATE FORMS OF UNCERTAIN PLACE

Between Flexibilia and Camerata.
Dicyclic; higher brachials incorporated in calyx by lateral union; calyx pliant, plates united by loose suture; pinnulate; IBB 5; IBr 2; no iBr except at anal side; anal plates in vertical succession, filling area and connected by suture with adjacent brachials . . *Cleiocrinus*
Between Flexibilia and Inadunata.
Dicyclic; 5 simple arms, free from radials up; except for small, irregular IBr of doubtful extent; habitus of *Symbathocrinus* . *Rhopalocrinus*
Base doubtful; arms dichotomous, branching many times; rays free from radials up, except for possible integument of small plates; anal side doubtful . . . . . *Caleidocrinus*

EXPLANATION OF PLATE IV

ONYCHOCRINUS ULRICHI M. and G.

FIG. 1.—The ventral disk or tegmen complete, except as to one ray, which is broken off; view from above, anterior side at the top. It shows the pyramid of four small orals at the center, two of them very plain, the third less so, and the fourth, at the left, pushed in under the others and invisible from this view; the large posterior oral with the ambulacra running along the sides, and the anal appendage bent over to the right under its posterior margin. The rows of ambulacral plates are seen extending from the oral pyramid to and along the rays, with the plated integument between them. The whole disk is now concave, having sunk down into the bottom of the calyx, and the view of the large posterior oral is somewhat foreshortened. The infolding ramules of the arms are well shown in two of the rays.

FIG. 2.—The disk of another specimen, seen from the under side—the calyx plates having been removed; posterior side up. This shows the same structures as Fig. 1, only viewed from the opposite side. The opening between the orals, and the undulating under surface of the posterior oral, are well shown; also the keeled inner surfaces of the ambulacrals.

FIG. 3.—Disk of another specimen, same view as in Fig. 1; showing the same structures, but with the curved anal appendage in plain view, and a portion of the plated integument, or perisome, attached to it at the right. The orals are much displaced, and the view of the posterior one greatly foreshortened; a row of strong plates proceeding from the shoulders of the posterior oral is well preserved in this specimen, perhaps serving as a brace for the tegmen.

FIG. 4.—Detail of central part of disk from another specimen; to show the perforate structure of the posterior oral. In order to get a better light on this plate, the specimen is drawn with posterior side up. This specimen shows but little aside from the posterior oral; the anterior orals are in position, in a more advanced stage of resorption than those in the other specimens; the round object at the right is probably a foreign body. The granules in the tegmen seem to be somewhat larger than usual. ×2.

FIG. 5.—Dorsal view of calyx and two complete rays, showing this aspect of the anal appendage.

THAUMATOCRINUS RENOVATUS P. H. Carpenter

FIG. 6.—View of the disk from above; showing the oral pyramid, the marginal zone of small plates between the orals and the interradials, and the anal tube with its appendage of strong plates. The protuberances seen between the arm-bases are the interradials, which separate the radials all around. (After P. H. Carpenter, *Philosophical Transactions*, Plate 71, Fig. 5. ×15.)

(All figures except 4 natural size).

EXPLANATION OF PLATE V

ANTEDON ROSACEUS

FIG. 1.—Early Pentacrinoid larva, spirit specimen, with its tentacular apparatus retracted; showing basals, radials, and rudimentary primibrachs, and the orals opened out. (From W. B. Carpenter, Plate XXXIX, Fig. 1A. ×15.)

FIG. 2.—The same, at a somewhat later stage, spirit specimen; showing incipient

development of arms from the IBr, and the relative increase in size of radials; cirri not yet developed. (W. B. Carpenter, Plate XXXIX, Fig. 1B. ×15.)

FIG. 3.—Skeleton of early Pentacrinoid larva at a little later stage, dried specimen; showing the manner in which the calyx can be, at that stage, completely closed by the folding together of the orals, *o*, *o;* cirri beginning to appear. (W. B. Carpenter Plate XXXIX, Fig. 2. ×35.)

FIG. 4.—Skeleton of Pentacrinoid larva, same stage as Fig. 2, dried specimen; showing anal plate *x* between two radials, and resting on the posterior basal. (W. B. Carpenter, Plate XLI, Fig. I. ×30.)

FIG. 5.—Skeleton of Pentacrinoid larva, in still later stage; showing the anal plate *x* now being lifted up from between the radials; cirri well started. (W. B. Carpenter, Plate XXXIX, Fig. 3. ×25.)

FIG. 6.—Pentacrinoid larva at a still later stage, when almost ready to cast off the stem. The anal plate *x* detached from the radials (which are nearly closed beneath it), and lifted from between them by the development of the anal tube *a*, to which it is attached; centrodorsal and cirri well developed. (W. B. Carpenter, Plate XL, Fig. 2. ×30.)

FIG. 7.—Opposite view of the same specimen, with one ray removed to show the oral apparatus. The orals, *o*, *o*, now completely separated from the radials, and relatively carried inward by the development of the membranous perisome, *p*. (W. B. Carpenter, Plate XL, Fig. 1. ×30.)

HOLOPUS RANGEI

FIG. 8.—View of the disk, with closed orals, *o*, *o*, perforated; and small plates at base separating the orals from the radials. (From P. H. Carpenter, *Chall. Rep. St. Cr.*, Plate III, Fig. 2. ×$\frac{5}{2}$.)

FIG. 9.—Hypothetical figure of primitive Flexibilia calyx; with infrabasals, radianal, anal *x* between radials, and two primibrachs.

EXPLANATION OF PLATE VI

(On this and the following plate the radianal is shaded with vertical lines.)

ICHTHYOCRINUS Conrad

FIG. 1.—*I. laevis* Conr. Upper Silurian, Grimsby, Canada.

FIG. 2.—*I. subangularis* Hall. Upper Silurian, Waldron, Ind.

FIG. 3.—*I. pyriformis.* Upper Silurian, Dudley, England.

FIG. 4.—*I. pyriformis* (fide Angelin). ×2. Upper Silurian, Gotland, Sweden. From original to Angelin's XXII, 22.

FIG. 5.—*I. intermedius* Ang. ×2. Upper Silurian, Gotland, Sweden.

FIG. 6.—*I. gotlandicus* W. and Sp. ×2. Upper Silurian, Gotland, Sweden.

These figures all show the extra plate—radianal—at the base of the right posterior ray.

CLIDOCHIRUS Angelin

FIG. 7.—*C. pyrum* Ang. Upper Silurian, Gotland, Sweden. View from right posterior radius.

FIG. 8.—View from posterior interradius of another specimen—the original to Angelin, XVII, 6.

ANISOCRINUS - Angelin

FIG. 9.—*A. interradiatus* Ang. Upper Silurian, Gotland, Sweden. Posterior, view; from original to Angelin, XXII, 18.

FIG. 10.—*A. angelini* W. and Sp. Upper Silurian, Gotland, Sweden. Posterior view. × 2.

FIG. 11.—*A. greenei* M. and G. sp. Upper Silurian, Louisville, Ky. Posterior view.

FIG. 12.—*A. oswegoensis* M. and G. sp. Upper Silurian, Oswego, Ill. Posterior view.

In all these the radianal is seen in primitive position directly below the right posterior ray.

LECANOCRINUS Hall

FIG. 13.—*L. macropetalus* Hall. Upper Silurian, Lockport, N. Y. Posterior view, showing radianal obliquely under right posterior radial.

FIG. 14.—*Ibid.* Anterior view of another specimen, to show absence of regular interbrachials.

METICHTHYOCRINUS n. g.

FIG. 15.—*M. burlingtonensis* Hall. L. Carboniferous, Burlington, Iowa. Without any radianal.

OLIGOCRINUS Springer

FIG. 16.—*O. asteriaeformis* Hall. L. Carboniferous, Burlington, Iowa. Anterior view of one of the type specimens; to show the mode of arm-branching.

PARICHTHYOCRINUS Springer.

FIG. 17.—*P. nobilis* W. and Sp. L. Carboniferous, Burlington, Iowa. Posterior view; anals in tubelike series.

NIPTEROCRINUS Wachsmuth

FIG. 18.—*N. wachsmuthi* M. and W. L. Carboniferous, Burlington, Iowa. Basal view; anal side not distinct; infrabasals probably coalesced.

WACHMUTHICRINUS Springer

FIG. 19.—*W. thiemei* Hall. L. Carboniferous, Burlington, Iowa. Basal view; no anal plates, but posterior basal in this specimen the largest.

(Figs. 4, 5, 6, 8, 9, and 11 after Liljevall.)

EXPLANATION OF PLATE VII

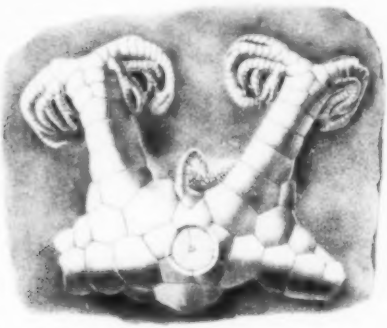
CALPIOCRINUS Angelin

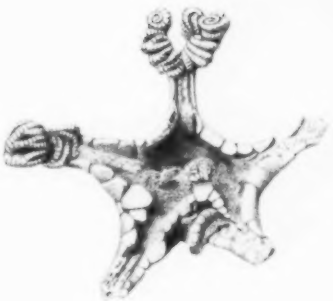
FIG. 1.—*C. fimbriatus* Ang. Upper Silurian, Gotland, Sweden. Anterior radial view; from original to Angelin, XXIX, 77.

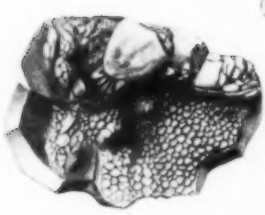
FIG. 2—*Ibid.* Basal view of same specimen; the infrabasals covering the basals except at the posterior side, but partly removed at two places to show points of other basals.

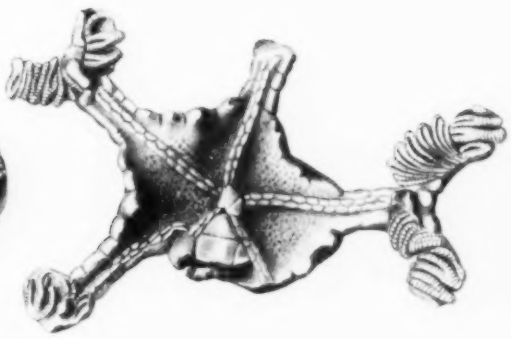
FIG. 3.—*C. heterodactylus* Ang. Upper Silurian, Gotland, Sweden. Basal view of calyx, with column ossicle attached; showing the enormous infrabasals, with posterior and two other basals visible as mere points.

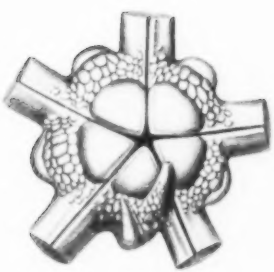
FIG. 4.—*C. ovatus* Ang. Upper Silurian, Gotland, Sweden. Basal view of calyx, from original to Angelin, XVI, 17–19; all basals except the posterior completely hidden by the infrabasals.

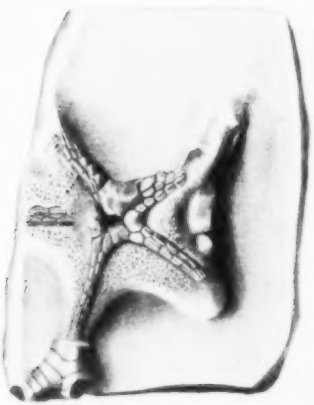


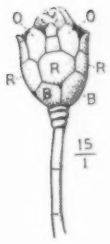












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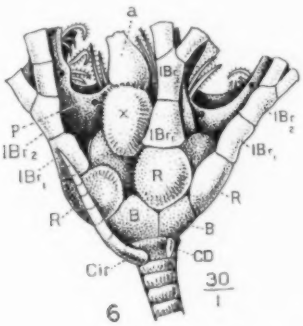

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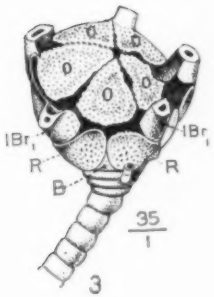

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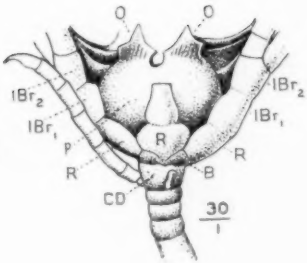

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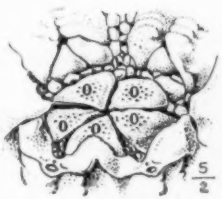

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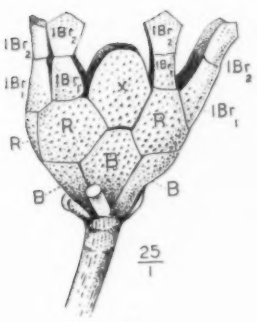

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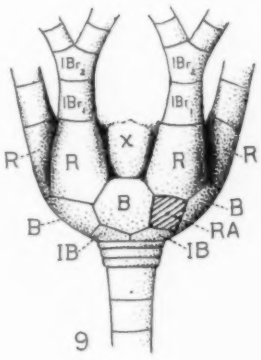

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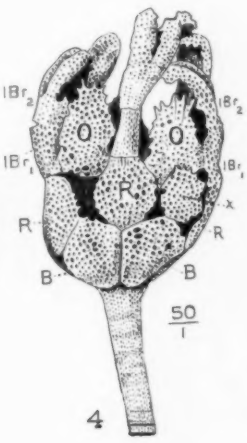

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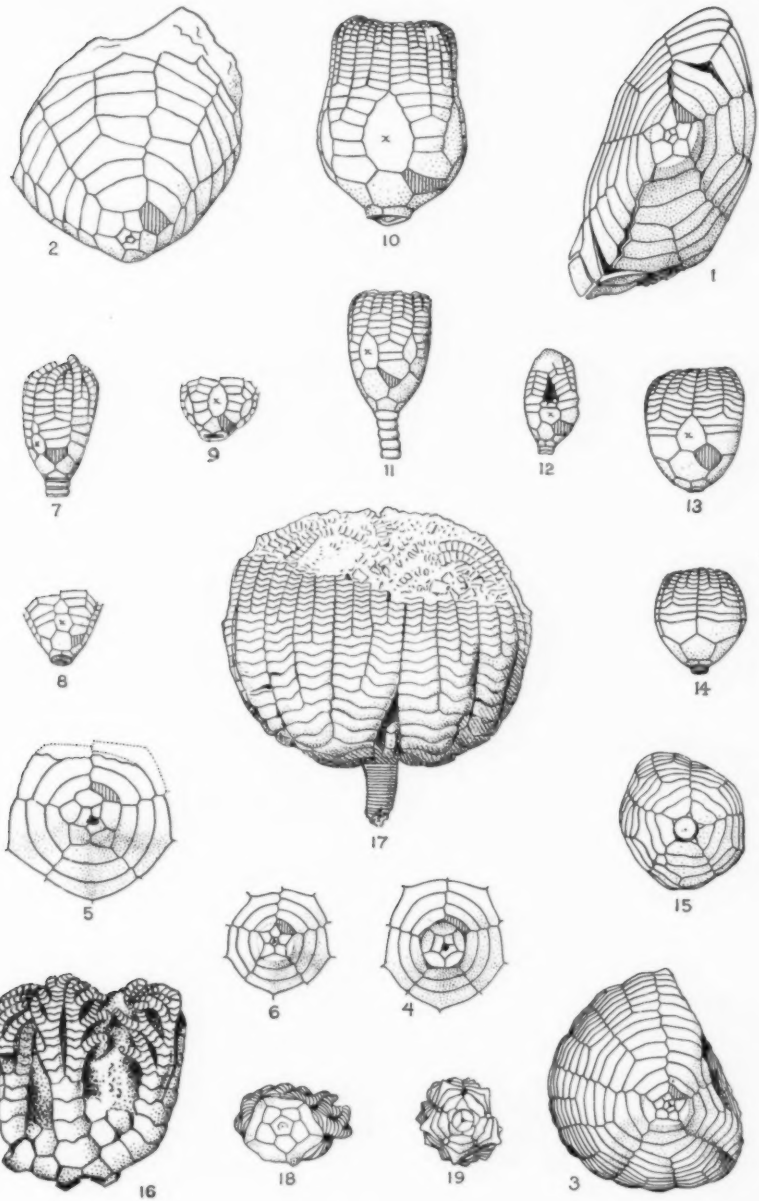
K. M. Chapman, Del.



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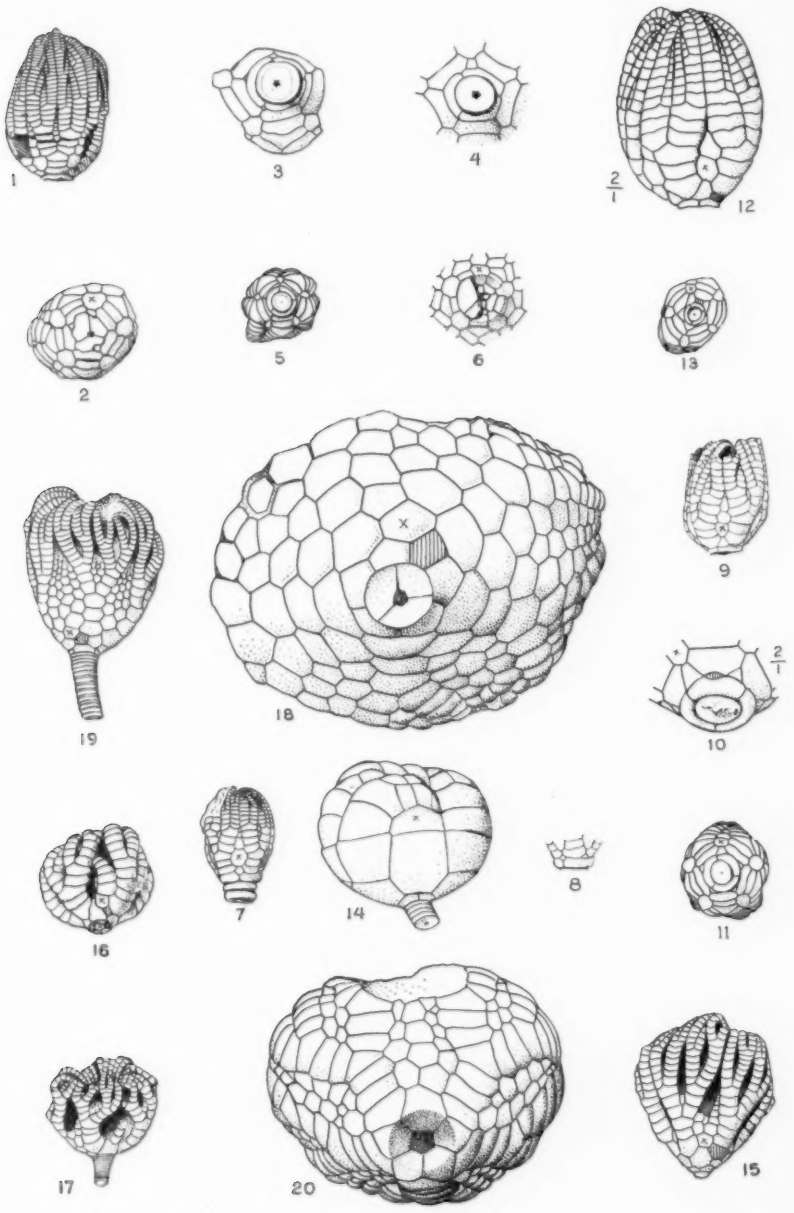

K. M. Chapman, Del.

FIG. 5.—*Ibid.* Basal view of another specimen, with column ossicle attached; no basal whatever visible.

FIG. 6.—*Ibid.* Basal view of another specimen; the infrabasals enveloping basals, radials, and part of first primibrachs. Part of the infrabasals have been removed, exposing the other plates beneath them, by which their relative positions and proportions can be seen.

FIG. 7.—*C. fimbriatus,* supra. Posterior view of crown with two column ossicles attached; from original to Angelin, XXIX, 77*b*.

FIG. 8.—*Ibid.* Left anterior radial view of base of same specimen; to show relative proportions of infrabasals and basals.

HOMALOCRINUS Angelin

FIG. 9.—*H. parabasalis* Ang. Upper Silurian, Gotland, Sweden. Posterior view of crown, from original to Angelin, XVI, 29; the very small radianal is visible, directly under the right posterior radial.

FIG. 10.—*Ibid.* Right posterior radial view of base of same specimen; showing radianal more distinctly. ×2.

FIG. 11.—*Ibid.* Basal view of same specimen, showing basals visible all around; radianal cannot be seen in this view. Nat.

FIG. 12.—*H. dudleyensis* n. sp. Upper Silurian. Dudley, England. Posterior view of crown, showing radianal directly under right posterior radial. ×2.

FIG. 13.—*Ibid.* Basal view of same specimen. Nat.

MESPILOCRINUS de Koninck and Lehon

FIG. 14.—*M. forbesianus* de Kon. and Leh. L. Carboniferous, Belgium. Posterior view; no radianal. (After de Kon. and Leh.)

TEMNOCRINUS Springer

FIG. 15.—*T. tuberculatus* Miller. Upper Silurian, Dudley, England. Posterior view of crown; radianal in primitive position as inferradial at base of right posterior ray.

GNORIMOCRINUS Wachsmuth and Springer

FIG. 16.—*Gn. expansus* Ang. Upper Silurian, Gotland, Sweden. Posterior view, from original to Angelin, XX, 16; anals in tubelike series; radianal obliquely under right posterior radial.

TAXOCRINUS Phillips

FIG. 17.—*T. shumardianus* Hall. Lower Carboniferous, Alabama. Posterior view; no radianal; anals in tubelike series, bordered by integument of small plates.

SAGENOCRINUS Austin

FIG. 18.—*S. expansus* Phill. Upper Silurian, Dudley, England. Basal view of a large specimen; radianal within the ring of basals and resting on the infrabasals; anal interredius perfectly filled with solid plates.

FIG 19.—*Ibid.* Right posterior view of smaller specimen.

FORBESIOCRINUS de Koninck and Lehon

FIG. 20.—*F. Washingtonensis* M. and G. L. Carboniferous, Indiana. Basal view of calyx; no radianal, and anal interradius perfectly filled with solid plates. The infrabasals are wanting in the specimen, having been detached with the stem, and fused with the proximal columnar.

(Figs. 1, 2, 7, 9, 10, 11, and 16 after Liljevall.)

STUDIES FOR STUDENTS

RELATIVE GEOLOGICAL IMPORTANCE OF CONTINENTAL LITTORAL, AND MARINE SEDIMENTATION

JOSEPH BARRELL
Yale University, New Haven, Conn.

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INTRODUCTION

The previous parts on the relative geological importance of continental, littoral, and marine sedimentation have shown that the bulk of present sedimentary deposits are formed either upon the land or beneath the sea, and that the littoral, restricted to its distinctive

limits as that belt of shore exposed between the highest and lowest monthly tides, forms but a relatively narrow transitional zone. Furthermore, it was shown that the chances for preserval of the true littoral deposits are but slight, for if the land is upraised, they are the most superficial deposits and the first to suffer erosion. If the land is slowly sinking, the margin of the sea moving across the land planes away the deposits made in advance of it to the limits of wave action, and this is ordinarily greater than the depth of the littoral deposits. Under these conditions the unlithified deposits formed in advance of the transgressing sea will only be preserved where protected in some manner from the work of the waves which follow.

The most favorable places for the development and also for the preserval of a broad littoral zone were found to be the frontal portions of the larger river deltas. In such places it has been seen that a slow subsidence frequently takes place *pari passu* with the accumulation of river-borne sediment, but the sea does not advance inland, and the littoral deposits are therefore not destroyed, but finally become buried to depths where they are beyond the reach of surface agencies and hence indefinitely preserved. But even in this case the littoral deposits form but a transitional zone between much more extensive and equally well-preserved marine deposits on the one hand and continental flood-plain deposits on the other.

It was furthermore shown that a considerable portion of the sediment of rivers was deposited not beneath the sea, but upon deltas facing and encroaching upon waters of the oceans or their outlying seas. This subaërial deposit of river waste upon deltas not only stands an excellent chance of preserval and incorporation into the geological record, but is ordinarily more important in area and volume than that of the littoral zone which borders it on the seaward side, and becomes most important where the deltas are broadly developed in shallow seas, since the deposits upon the delta surface hold under such conditions, a greater ratio to those deposited in advance of the delta. Even disregarding other important forms of continental deposits, the magnitude of subaërial deltas and the relatively small quantity of the littoral deposits which will be preserved indicate that a much larger place should be given to fluvi-

on the northern flank of Mount Ellsworth.[1] The formation of these mud-cracks was followed by a complete change of sedimentation at this point into the homogeneous sandstones of the Vermilion cliff group, so that it is quite certain here that the mud-cracks were not formed in the brief interval between two similar tidal invasions. So little is known, however, of the relations between the governing conditions and the characteristics of the mud-cracks that, in the absence of more data, this detailed subject cannot be profitably discussed, and the attention will therefore be turned to the various conditions under which they originate and the associated chemical, textural, and structural features which accompany them in each case.

Such conditions are observed to obtain first, over playas and temporary lakes of arid regions; second, upon the margins of interior lakes; since the latter are peculiarly liable to seasonal fluctuation in level; third, over many river plains as a result of the periodical floods in places where the surfaces are not covered with an arboreal vegetation; fourth, over the higher portions of the littoral zone, where mud-flats or tidal marshes are exposed to the air sufficiently long for the mud-cracks to originate. The littoral in the previous article has been limited to the level which is flooded on the average twice per month by the tides of the new and full moon, since above this limit the tidal flooding is in a manner accidental and occasional and only occurs during abnormally high tides or storms. Mud-cracks will therefore be formed also over an adjacent portion of the continental zone due to unusual elevations of the level of the sea.

CONDITIONS FOR TEMPORARY PRESERVAL OF MUD-CRACKS

Before taking up the detailed discussion of the conditions of origin, relation to other features, and final preserval of mud-cracks, it is desirable to state some conclusions which the writer has reached from observation and experiment upon the conditions necessary for the temporary preserval of the cracks until the stratum shall become buried and form no longer the surface layer.

Experiments were conducted first upon interstratified light brown silty clay and dark brown clay of Champlain age; the former smooth to the fingers, but giving a fine grit to the teeth; the latter

[1] *Geology of the Henry Mountains* (1877), p. 9.

perfectly smooth to the teeth. Second, upon a modeling clay giving a fine grit and third, upon clay from New Haven harbor, gray-black when wet, light gray when dry, giving a very small amount of fine grit to the teeth. Lack of time did not permit accurate soil analyses to be made of these types.

The Champlain silty clay, firm and strong when removed from the clay pit, was dried and then covered with water. Within from five to ten minutes a stratum half an inch in thickness would soften, swell, and begin to disintegrate, losing all coherency, turning to a creamy mud and the margins sliding down to the angle of repose. The clay and silty clay were then ground up, mixed in nearly equal proportions, allowed to settle in pans from water and dried in the sun. After becoming thoroughly dry and cracked, two out of three pans were baked over gas, one at a temperature up to 70° C., the other above 100° C. This was done in order to test the effects of drying at and beyond the most extreme temperatures of torrid deserts. Upon being covered with water, the swelling and disintegration took place as before, indicating that a mixture of equal parts of pure clay with silty clay would not preserve the stratum from disintegration, and that the highest ranges of temperature found in nature were equally ineffective. Upon drying, cracking, and then rewetting, the lines of the cracks are partly closed by swelling. The remainder becomes filled and veiled with a more fluid mixture, and upon redrying the cracks are established chiefly upon the same lines, indicating a weaker cohesion along the lines of previous cracks. The same feature was observed in the field after a rainstorm, the deeper parts of the cracks having been closed by swelling, but still forming lines of weakness; the upper parts blurred by the slaking of the mud. Upon wetting in the laboratory, adding a new layer, and redrying, the two layers adhered as a unit, and the cracks were twice as widely spaced. Those which formed, however, followed in general previous lines of cracking, and those cracks which did not reopen were still to a slight extent lines of weakness. Finally, the pure clay in strata half an inch in thickness was dried for a couple of weeks at ordinary temperatures, broken, and placed in water. They gradually softened in the course of an hour, but for days retained their sharp edges and showed no tendency to disintegrate, though swelling 5 per cent.

on the northern flank of Mount Ellsworth.[1] The formation of these mud-cracks was followed by a complete change of sedimentation at this point into the homogeneous sandstones of the Vermilion cliff group, so that it is quite certain here that the mud-cracks were not formed in the brief interval between two similar tidal invasions. So little is known, however, of the relations between the governing conditions and the characteristics of the mud-cracks that, in the absence of more data, this detailed subject cannot be profitably discussed, and the attention will therefore be turned to the various conditions under which they originate and the associated chemical, textural, and structural features which accompany them in each case.

Such conditions are observed to obtain first, over playas and temporary lakes of arid regions; second, upon the margins of interior lakes; since the latter are peculiarly liable to seasonal fluctuation in level; third, over many river plains as a result of the periodical floods in places where the surfaces are not covered with an arboreal vegetation; fourth, over the higher portions of the littoral zone, where mud-flats or tidal marshes are exposed to the air sufficiently long for the mud-cracks to originate. The littoral in the previous article has been limited to the level which is flooded on the average twice per month by the tides of the new and full moon, since above this limit the tidal flooding is in a manner accidental and occasional and only occurs during abnormally high tides or storms. Mud-cracks will therefore be formed also over an adjacent portion of the continental zone due to unusual elevations of the level of the sea.

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Experiments were conducted first upon interstratified light brown silty clay and dark brown clay of Champlain age; the former smooth to the fingers, but giving a fine grit to the teeth; the latter

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linearly upon the plane of stratification. When rubbed to a batter in water and allowed to dry and crack, the edges disintegrated and the cake softened more rapidly, indicating that the original closer-knit texture had given it superior resistance. Drying and baking up to the boiling-point did not affect the result.

The modeling clay was not baked, but, in all respects tested, behaved like the mixtures of Champlain clay and silty clay.

Finally in August, 1906, excellent opportunities were offered for observing the behavior of the unctious and sticky gray mud of New Haven harbor; a reclamation company building turf walls around many acres of salt marsh land, and pumping water, mud, and sand from the center of the harbor into these artificial reservoirs, the sediment settling and the water draining away. In this way from 6 to 20 feet of sediment were laid down under most favorable conditions for observation. It was found that from mid July to mid August beds of gray mud up to a foot in thickness, resting upon sand, had dried and cracked into irregular polygons 1, 2, and even 3 feet in diameter, the cracks opening from 3 to 4 inches.

Where the mud was thicker, the bottom was still soft, but the top was cracked. Where the water was still standing no cracks had formed, but upon the disappearance of the water they began to appear as wedge-shaped cracks, while the top clay was still soft to the hand and the bottom so fluid as to make walking impossible.

These cracks had formed and the clay underlain by sand had dried and hardened to the depth of a foot during an interval, as stated, from mid July to mid August, during which time the mean temperature was 71° F., the average humidity 0.83, the precipitation, in thirty-one days, 3.0 inches, ten days partly cloudy, and twelve days cloudy.

Rain had failed to efface these cracks, though washing more or less mud into them, especially when the cracks were still young and narrow and the clay not yet hardened. Reflooding by pumping was observed to soften the clay to the consistency of a stiff gelatine and expand it somewhat, but did not obliterate the sharpness of the cracks even in the course of days; and where mud or sand was washed over the surface, the cracks were permanently buried and preserved. Where filled with similar mud and redried, the filling may be detected,

even where the crack fails to reopen, by the interruption of the faint lines of stratification at the margins and a slightly marked weakness along this line. When this mud was beaten up with the water, dried quickly over gas and then recovered with water, the air rapidly escaping from the many minute bubbles produced an audible simmering, and the mud, originally so retentive of its form, soon fell into a mush. It was also observed that the dry natural clay was subject to a slight exfoliation upon rapid wetting. These facts point out the importance of close texture, obtained by slow subsidence and long standing under water before drying. This requires the moisture to be transmitted slowly, by capillary action, and allows the mass to expand as a whole.

The conclusions from these observations and experiments will doubtless be somewhat modified by more extensive observations in suitable regions, but may be preliminarily stated as follows:

A mud-cracked loam or silty clay, even when the sand particles are imperceptible to the fingers, is an unfavorable material for the preservation of its detailed surface structures, except possibly when remaining moist, so that but little swelling and exfoliation take place. Upon being wet by rain, the rapid swelling and disintegration of the surface stratum would turn the surface of such a deposit into a creamy mud, which, if remaining *in situ*, might preserve upon redrying blurred impressions of the previous cracks and other larger surface features, but which would be peculiarly liable to be swept away and intermingled with the detritus of the following flood similar to the one which left the material. Even if the flood sweeps down from the mountains upon previously unwet desert plains, the few minutes of wetting necessary would suffice to destroy the detail of surface features before a sufficient new layer of sediment could be laid down. This would seem to explain the mud-lakes into which many playas are transformed during the rainy season. Upon such a formation becoming lithified, the record of mud-cracks might be greatly masked, if not entirely obliterated. The development of joint planes, and even a faint cleavage, would add to the difficulty of detection. Where the finer details of the original surface are preserved, however, or the sharp surfaces of stratification between unlike laminæ, it would seem impossible that the mud-cracks could

become completely obliterated. This, therefore, may be a test as to their former presence or absence.

A pure clay, slowly subsiding from quiet waters, and wet sufficiently long to become compact upon drying, would retain its mud-cracks upon rewetting, either by rain previous to flooding or by the flood waters themselves. Such a clay, on account of its tenacity, resists erosion even by quite rapid currents, as is seen from the presence of occasional areas of sticky blue mud on relatively shallow and open parts of the coastal shelf. In case such a sun-baked clay is covered and its cracks filled by a similar layer, it should retain a clear record of the cracks, provided it possesses a well-defined bedding cleavage, since such a cleavage will be interrupted at the margins of the cracks. Such pure and massive clay deposits form, however, the rocks most susceptible to dynamic metamorphism, and a pressure cleavage, even if developed upon the bedding planes, would tend to mask any previous interruptions. Frequently, however, such clay deposits from standing water will be interstratified with more or less arenaceous deposits swept along the bottom by the rising floods. Such sandy wash filling the cracks of the previous clay layer would give a persistent record to the buried mud-cracks. If the sand be sufficiently coarse not to shrink markedly upon drying or swell upon rewetting, the combination of the two kinds of laminæ should give a maximum opportunity for the complete preserval of mud-cracks, footprints, raindrops, and other surface markings. It is noteworthy that this is the typical nature of those beds in the Triassic formations of the Connecticut valley which have preserved such a magnificent record of mud-cracks and footprints. Large portions of these formations, however, consist of rather massive sandy shales or arkoses, and in these the writer has not noted the occurrence of mud-cracks.

On the larger river flood-plains, such as that of the Mississippi, the soil survey of the Department of Agriculture has established three principal types, grouped under the Yazoo series and seven miscellaneous types. Of these ten types only two are clays. The Yazoo clay—a heavy, drab clay loam—occupies low areas back from the low, flat ridges which form the front lands near the stream courses. It is a frequent type of soil. The Sharkey clay is a stiff, impervious clay occupying the lowest portions of river bottoms

and subject to annual overflow. Both are characterized by sun-cracks—a characteristic not ascribed to the other types of soil. It is noteworthy that the purer clay, and therefore that more favorable for the preservation of mud-cracks, is deposited, not from flowing, but rather from stagnant back waters, the one at high-water stage, the other when the water-level is lower. Only a portion of the deposits of the larger flood-plains are, therefore, well fitted to retain surface impressions until buried, and this principle must be carried into the past.

It is seen that mud-cracks may originate in pluvial climates, but the thick mat of vegetation apt to form under such conditions would tend, wherever it existed by the binding action of the roots, to prevent cracks from forming. An arid valley climate, therefore, and abundant sediment would be more favorable conditions for the broad development of mud-cracks. Rock decomposition, rather than disintegration at the sources of supply, the mark of a pluvial climate, should, on the other hand, be favorable as furnishing a larger proportion of pure clay mixed with the coarser material.

In conclusion, it is seen that special conditions are necessary for a complete temporary preserval of mud-cracked surfaces even where continued sedimentation without intervening erosion occurs. In formations which show traces of mud-cracks it is to be anticipated that other, more or less argillaceous layers may also have been exposed to the air. Sediments swept along by broad, slow-moving waters will ordinarily possess too much loam for the good preserval of mud-cracks. But where the flood waters stand quietly before being drained away, or where the loam is strained out or settles at another place, the fine clay will settle, forming a deposit free from sand, and capable of retaining even the faintest markings made upon its drying sufrace.

MUD-CRACKS OF PLAYAS

Description.—The characteristics of these may be best appreciated by quoting from Russell's descriptions of the present and extinct lakes of Nevada.[1] Speaking of the ephemeral lakes forming either after the rainy season or even after a single storm he says:

[1] *The Physiography of the United States* (American Book Co.), Monograph 4, pp. 105–10.

Should the storm continue, the sheets of water in the valleys will expand, and possibly become many square miles in area. Such lakes are always shallow, and always yellow with mud in suspension. When the sun breaks through the storm clouds, evaporation becomes active, and the lakes gradually contract their boundaries, and perhaps in a few hours or in a few days are entirely dissipated. When the water has disappeared, absolutely barren mud plains remain, which harden under the sun's heat, and become cracked in all directions as their surface contracts in drying. The lake beds then have a striking resemblance to tesselated pavements of cream-colored marble, and soon become so hard that they ring beneath the hoof beats of a galloping horse, but retain scarcely a trace of his foot-prints.

Such bare, level mud plains are characteristic features of the greater part of the valleys of Nevada, and are known in Mexico and adjacent portions of the United States as playas. The lakes to which they owe their origin are termed playa lakes. . . . . The largest ephemeral lake of Nevada is formed during winter months on what is known as Black Rock Desert in the northwestern part of the State. This desert valley is irregular in shape, and has lateral valleys opening from it. Its length from northeast to southwest is over one hundred miles, and its average breadth twelve or fifteen miles. In summer it is almost entirely without tributary streams, except such as are fed by hot springs. In winter many brooks descend the mountains to the east and west; and the channel of Quinn River, which enters the basin from the northeast, is transformed into a veritable river. The course of this stream in summer is marked only by a dry channel, with an occasional water hole; but in winter it is flooded so as frequently to be impassable to a man on horseback, and has a length of upward of a hundred miles. Its waters then spread out on Black Rock Desert, and at times form a long narrow lake from 450 to 500 square miles in area. Although seldom over a few inches deep, it is impassable on account of the softness of the mud forming its bottom. Many times the "lake" is a vast sheet of liquid mud, and for this reason is known as "Mud Lake" by the settlers of the region. This name is not distinctive, however, as many other playas have the same name attached to them. . . . .

The winter lakes on Black Rock and Smoke Creek deserts, as in many other similar instances, do not occupy the entire valley bottom, but are surrounded by a broad fringe of what to the eye appears level land. This broadening tract is covered with sagebrush and other desert shrubs. In early spring many flowers beautify the ground, and fill the air with a faint perfume. The playas left by the desiccation of the lake, however, are always barren. Not a plant takes root in their baked and hardened surfaces. Where these mud-plains meet the surrounding areas clothed with desert shrubs, there is often a belt of ground that is soft and marshy in winter, and frequently retains something of this character after the lakes have disappeared. In summer it becomes white with salts brought from below by ascending water, and left on the surface when evaporation takes place. These efflorescent deposits become unusually abundant

about some of the hot springs, and are then apt to contain borax in addition to the sulphate and carbonate of soda, common salt, etc., which make up the bulk of such incrustations. . . . .

North Carson and South Carson lakes are of the playa type, but are more persistent than the lakes of Black Rock and Smoke Creek deserts. They sometimes hold their integrity for a succession of years, but evaporate to dryness during seasons of more than usual aridity. North Carson Lake is rudely elliptical in outline, and is from 20 to 25 miles across from east to west, and about 14 miles broad from north to south. That its depth is never over a few feet, has been shown by examining its bed when dry. . . . .

Hundreds of other inclosed basins, particularly in southern Nevada, are partially flooded in winter in a similar manner to those already enumerated, and become desert plains of hardened mud in summer. Various portions of the region surrounding Nevada, and especially those embraced within the boundaries of Utah, Arizona, and California, experience changes similar to those just described, and illustrate some of the most striking peculiarities of a region where the topographic and climatic conditions favor the existence of temporary lakes.

Numerous playa lakes are also found in Australia and in Africa, especially in the Kalahari, and may be looked upon as common features of desert regions where the regolith is not sufficiently deep and sandy to absorb all of the occasionally precipitated water. Playa formations are not necessarily accompanied by conspicuous saline deposits since the clay washed in, and subsiding each year prevents re-solution of the buried salts and may largely exceed them in quantity. The amount of salt will also depend upon the area of the playa to the catchment area and the extent to which ground water contributes. In old desert regions such as the Kalihari there may be thus wide playa surfaces where water stands for a longer or shorter period. Speaking of the Kalihari, Brewer states that "Lake Ngami is fresh in the rainy season, but covers much less surface in the dry season, and is then brackish; and the other lakes of this desert are described as brackish rather than salt."[1]

Nature of the geological records.—The preceding is a description of playa surfaces. In the absence of descriptions of partially eroded playa deposits seen in cross-section the following statement of the characteristics which they would presumably show when incorporated into the geological record must be to some extent deductive and open to corroboration by observation.

[1] Wm. H. Brewer, *Warren's New Physical Geography.*

Playas will be flooded with water partly by means of stream channels, partly by a general wash from the outside over the slopes, partly by a gradual rise of the water level flooding the surface from the inside. In places of inflowing currents, the cracks should fill up with sand and thereby permanently preserve the structure; in places where clay settles in from quiet water, the infiltration may be almost identically the character of the wall materials and the former presence of the crack therefore escape record. The water stands over the flat bottom in periods varying from a few days to a few years, according as to whether it is an evanescent playa or one dry only during an occasional year. The periods of desiccation will vary in inverse order. In general, however, it may be said that the playa bottoms become thoroughly wet for a depth of several feet and undergo some months of desiccation with the formation of deep mud-cracks. Where the deposits are perfectly homogeneous and result in massive saline clays there may be no permanent record of the cracks. As playas are characteristic of typically desert regions there is but little likelihood of the incorporation of an organic record, either of leaves, bones, or tracks. As embodied in the geological record playas should occupy the centers of flat basins in mature desert regions, and in that case their deposits may conceivably attain a thickness of several thousand feet as the mountains are gradually leveled off and their waste accumulated in the tectonic intermontane troughs. Such deposits as seen in cross-section would pass irregularly into marginal waste slopes of coarser material and these in turn end unconformably against the sloping walls of the buried portion of the mountains. Thus their basin nature and limited extent would be evident.

Unless protected, however, by an invasion of the sea or a change to a pluvial climate such deposits as well as the intermediate rocky barriers will gradually be removed by deflation, as Passarge has shown,[1] and the desert will pass into the stages of old age as exemplified by the Kalihari. Throughout this process of erosion shallow playas play an important rôle, since the occasional rains wash the surrounding waste into them and thus tend to maintain a level

[1] "Rumpfflächen und Inselberg," *Zeitsch. deut. geol. Gesellsch.*, LVI (1904), Protokol., pp. 193–209. Review by W. M. Davis, *Science*, N. S., Vol.XXI, p. 825.

surface. But such deposits must be very shallow since as soon as insolation and deflation have lowered the surrounding tracts these in turn become playa basins and the waste of the former one suffers removal.

Thus ancient playa deposits may be of importance in certain intermontane desert basins of the Tertiary or earlier periods, now suffering stream dissection and exposure, but those of topographically old deserts can be of no importance except possibly as the occasional surface veneer of an ancient continent, such as that of the pre-Cambrian, when it passes unconformably beneath the deposits formed by a marine transgression. In such an event, however, they would doubtless be partly destroyed through marine planation.

MUD-CRACKS MARGINAL TO INTERIOR LAKES

Description.—There are many regions of the world showing all transitions between true salt lakes and fresh-water lakes with perennial outflow.

Where evaporation does not quite balance the inflow of water there may be an occasional discharge, either at the end of the rainy season or only during a series of rainy years. Such lakes without being salt show fluctuating shores, usually very flat, since the water does not stand sufficiently long at one level for the characteristic beach slopes to form. Wide expanses, therefore, may become sun-cracked and thoroughly hardened before the next rise of the lake waters occurs and deposits over them another layer of clay.

Prominent examples of this class of lakes are Titicaca in South America, 80 miles long by 40 broad, and Lakes Tanganyika and Tchad in Africa. Lake Sistan in Persia with a breadth of 60 miles and a length of 100 has been known to go completely dry, while in occasional years during times of heavy flood it sends a stream of water down the Shila.

Nature of the geological record.—In some respects the structures recorded in the formation of the successive laminæ will be similar to playas, but differ in that the exposed area is a transitional belt between a relatively permanent water body and a permanent land surface with its wind and stream-borne detritus. It is more subject to wave-action, building occasional beaches; it may not be salt

and may be the seat of a considerable assemblage of living forms. The result is that the lake clays need not be saline, but are likely to be leached of iron or be even carbonaceous and fossiliferous. Footprints may also be common on the shores and the remains of land plants, and animals may become entombed in the deposits. The wash of nearby land waste and the action of waves may fill up the mud-cracks with sand and thus lead to their permanent preservation.

Interior seas are unstable bodies whose shores are ever varying, and which are finally destined to be either dried up into playas, the fate of Lake Lahontan, or to be filled up with sediment, giving rise to river flood-plains, the fate at present overtaking Lake Titicaca, or by becoming fresh to be drained by cutting down an outlet, a change at present in progress in several of the large African lakes.[1] As seen in geological section the mud-cracked margin should be transitional on any one horizon between fine-grained, paper-thin, lake clays, on the one hand, showing no mud-cracks, and the coarser slopes of land waste on the other. In ascending through the formation such mud-cracked shales should oscillate laterally and occupy but a portion of the series. They could hardly, therefore, be a characteristic feature of the sediments in general, nor even of the bodies of shales originating in the lakes of interior basins.

MUD-CRACKS OF RIVER FLOOD-PLAINS

Description of present conditions.—Over all river flood-plains inundations periodically take place, and as the flood waters gradually drain away, a large quantity of fine mud is left upon the surface, perpetually renewing the fertility of the soil. Where the climate is humid, as over the delta of the Mississippi, such regions become seats of luxuriant verdure, while on the contrary in arid or semi-arid regions, an evanescent vegetation may spring up following the flood, but as soon as the water is drained away and the level of the ground water sinks beyond the reach of the plant roots the region becomes a desert until the period of the next inundation. Such regions are abundant over the desert belt of the world, the flood plains of Egypt, of Mesopotamia, and of the Indus River being

[1] Albrecht Penck, "Climatic Features in the Land Surface, *American Journal Science*, Vol. XIX, p. 171 (1905).

familiar examples.[1] In such regions the conditions of mud-crack formation are at a maximum and may extend to the margin of the littoral zone.[2] Consequently carbonaceous deposits and mud-cracks both mark the land surfaces of aggrading rivers, the one a maximum in pluvial climates, the other in arid. Mud-cracks, as contrasted with coal beds, may thus serve as an index to ancient climates as well as possessing a stratigraphic significance.

In applying this distinction to the earlier geological periods it should be held in mind, however, that there is no evidence of an arboreal or even herbaceous vegetable covering to the land previous to the Silurian, and its surface was presumably devoid of life save possibly that of the lowest cryptogams. Under such circumstances the indications of the presence of former flood-plain surfaces by means of carbonaceous deposits or deoxidizing effects upon the ferric oxide might be entirely absent. Mud-cracks would be the safest remaining indication of the flood-plain nature of the land surface over the regions where the character of the detritus was suitable and periods of desiccation were sufficiently long for the formation of the cracks and hardening of the successive surface layers.

The necessary fineness of deposit is frequently not found on the sandy or gravelly fans of mountain streams, and hence a large per cent. of stream-built deposits could not be expected to show this feature. The necessary conditions are found, however, on all streams of small gradient which broadly overflow their channels, this being characteristically the case of the larger rivers in the lower portions of their courses and especially over the delta, where the argillaceous nature of the deposits is well known. Broadly speaking then, the formation of mud-cracks is non-essential on slopes of piedmont river waste, but is especially characteristic of the larger river plain and delta deposits of arid and subarid climates. That the phenomenon is not strictly confined to even subarid climates is, however, true since humid climates may have their seasons of dryness.

[1] See for illustration, Daniel Trembly Macdougal, "The Delta of the Rio Colorado" (with map by Godfrey Sykes), *American Geographical Society*, Jan. '06.

[2] Walther, *Das Getz der Wüstenbildung*, 1900, also mentions the occurrence of mud-cracks on arid flood-plains. See *Trockenrissen* in index.

Nature of the geological record.—Flood-plains differ from playas and the shores of interior lakes in important particulars. Playas are formed in local basins or as the ends of desert rivers, usually of limited length. Playas do not fill up valleys from which the rivers escape, but are entirely phenomena of interior drainage. They are not built out against the sea and the deposits are at least brackish from the inclosed salts.

The flood-plain of an aggrading river covers a wide area, in the case of the larger rivers measured by thousands of square miles. It is all periodically subject to inundations which may last for a few days or weeks, but leave the greater part of the surface exposed to the air during much of the year. The invading flood waters frequently sweep sand with them, but after the flood is at its height the waters drain away quietly and much of the fine clay is deposited from suspension. Thus on river flood-plains there is peculiar liability to form well-interstratified deposits of sand and clay: to fill up the last-formed mud-cracks with coarser material, and hence permanently to record them through the varying composition and structure of the formation. Such successive strata of the same nature may be indefinitely accumulated.

Such valleys even in desert regions commonly support considerable life. Drifting vegetation is liable to become buried and animals crossing the half-dried flats in search of fresh water may leave through their foot-prints a record of their visits. The periods of desiccation are seasonal and sufficient to harden this record of cracks, rain-prints, and foot-prints to such an extent that the next invasion of water does not wash it out, but by depositing upon it a new layer of sediment permanently preserves it. As the main streams or their distributaries wander over the plain from century to century they form a network of channels which cut through the preceding fine-grained layers of the flood-plains, and the channels become filled with sand or even gravel, as they are finally abandoned for new courses. They may be distinguished from the beach sands and gravels of lakes from their linear, treelike arrangement, their occasional cutting-down into the finer-graind layers, and their occurrence far from the margins of the basin.

The mud-cracked strata of flood-plains not only stand excellent

chances of temporary preserval until buried, but since the surfaces upon which the fine-grained river waste is deposited are ordinarily near the level of the sea and are also in the case of the greater deposits frequently regions of subsidence, the chances for ultimate preserval of the bulk of the formation is, in such cases, as favorable as that of the true marine shallow-water deposits.

Again, flood-plain surfaces are not of a transitional or temporary geological nature, like the margins of interior lakes, or the borders of the sea, but they are the ultimate physiographic forms toward which both lakes and shallow seas tend by the filling-in of river waste. They are of broad occurrence at all times of continental extension and erosion, and should be looked for in the geological column as only second in importance to the off-shore deposits of the continental shelves and seas. But although flood-plains are most commonly built near the margins of the land and encroaching as deltas upon shallow seas, they are also found to occur over the regions of gräben or troughs of subsidence, such as those of the Rhine, and of other tectonic valleys, and also over interior basins. Murray has estimated the desert areas, that is those which do not drain to the sea, as one-fifth of the continental areas. Doubtless, at least another fifth is possessed of a climate marked by sufficient seasons of drought to allow the broad formation of mud-cracks upon flood-plains, following the subsidence of the flood waters.

This natural condition is, however, largely modified at the present time by the agency of man, since, by regulating the floods and by systems of irrigation, such regions become the seat of populous societies. It has been shown in the previous article that the deposits of flood-plains should enter more largely into the geological record than is usually appreciated. Combining this conclusion with these considerations in regard to climate it is seen that in those past times, which corresponded in general to present conditions, an appreciable fraction of argillaceous deposits should be characterized by mud-cracks formed upon flood-plains, and, on the other hand, in regions where the mud-cracks of the period are missing, another appreciable fraction should by their carbonaceous and organic contents bear witness of the verdure which prevails upon the river plains of pluvial climates.

Besides these general stratigraphical relations which should characterize the mud-cracked deposits of arid flood-plains may be mentioned other associated characteristics, some of which are pointed out by Walther.[1] Such deposits are usually rather barren of fossils of water-living forms; the latter, if present, are apt to be restricted to the lines of sandstone which mark the ancient channels[2] or to the deposits of shallow lagoons. The flood plain proper is more likely to contain the remains of air-breathing forms, but as conditions must have been frequently unfavorable for their life or for their preserval after death the strata are more usually barren.

Further, land deposits on account of the local and annual variations of conditions are apt to show various sorts of deposits—water borne, wind borne, organic, and volcanic, in close association but differentiated from each other. Marine deposits are not subject to this rapid variation and more gradual transitions are observed.

Deposits formed in rivers or in lakes and seas have usually greenish or bluish shades of color as in marine deposits. Those subjected to subaërial exposure, however, under arid or subarid conditions are apt to possess a normal content of iron owing to the absence of carbon and the opportunity for complete oxidation following the subsidence of the ground water. The river muds from which the iron has not been leached by the deoxidizing influence of vegetation may thus be yellow, brown, or red. In well-lithified but still unmetamorphosed formations, in which the iron still exists in the form of a free oxide, reds predominate, whereas in modern muds derived from the crosion of granite lands yellow or brown is observed to be the prevailing color. But Crosby[3] has shown that a gradual dehydration of the ferric oxide serves to transform colors originally yellow and brown into deep red or vermilion.

River deltas normally contain abandoned channels or lower tracts of country not yet built up which are more or less permanently flooded with fresh water. Such are usually the seats of luxuriant vegetable growth and abundant animal life, even under climates where the

[1] *Einleitung in die Geologie* (1893), pp. 719–26.

[2] J. B. Hatcher, "Origin of the Oligocene and Miocene Deposits of the Great Plains," *American Philosophical Society*, Vol. XLI (1902).

[3] "On the Contrast in Color of the Soils of High and Low Latitudes," *American Geologist*, Vol. VIII (1891), pp. 72–82.

other portions of the delta may be dry and barren during a greater portion of the year. The decaying material of such fresh-water swamps, being preserved by the water covering, will serve to deoxidize the iron to the ferrous state, and even if the carbon is not sufficient in amount to color by its balance the argillaceous strata to brown or black, its former presence will still be indicated by gray or green bands of shales. Thus delta regions of subarid climates are peculiarly liable to be forming deposits which will ultimately become variegated shales, in which maroon, deep red, or vermilion bands will pass, sometimes almost without change of texture, into bands of grayish-white or green. An example of such variegated strata recently made is described by Huntingdon as having formed in the basin of eastern Persia and Sistan.[1]

The seaward portion of the delta surface is also frequently covered between the distributaries by brackish or salt-water lagoons and bays, as in the Nile and Mississippi deltas, protected from the waves and possibly containing considerable life of estuarine types, whose decay will lead in the same manner to variegated shales.

In truly arid climates, however, such river or sea lagoons are the seats of progressive evaporation giving rise to such salt pools as front the northern portion of the Caspian Sea or the recent gypsum deposits of the Isthmus of Suez. The degree of aridity and of the severance of the lagoons from the sea will determine the kind and amount of the chemical precipitation. It would seem, therefore, that the mud-cracked red beds originating on the delta surface of an arid climate should frequently be interstratified with mud-cracked beds holding salt or gypsum, a less arid condition leading more usually to the production of variegated shales.

MUD-CRACKS OF THE LITTORAL ZONE

Discussion as to present origin.—The littoral zone is one of the most sharply delimited of the natural physiographic divisions, forming a narrow belt between the sea and the land and defined here as comprising the zone between the average highest and lowest tides of the month. To form mud-cracks the deposit must be exposed to the sun or air sufficiently long to be dried out to such a depth

[1] *Carnegie Institution Publications* (1905), pp. 285 ff.

that the underground capillary rise is no longer able to keep the surface wet. This time limit will vary with the climate and the texture of the clay, but there may be immediately excluded all that portion of the littoral which is wet twice per day; in other words, all that portion of the littoral below the upper limit of the neap tides. This may be modified to some extent by strong off-shore winds. In the temperate zone such winds, being usually of a cyclonic nature, are frequently accompanied by rain; but where not, it is possible that by this means the tidal rise may be prevented from reaching its normal level by some feet and mud-cracks formed in the meantime somewhat below the usual level. In the latitudes of monsoon winds such effects might be seasonal, as is noted in the Runn of Cutch on the southeastern side of the Indus delta. Off-shore winds, therefore, will permit a wider development of mud-cracks over the upper portion of the littoral zone, but it is not probable than any appreciable areas below the level of mid-tide should be laid bare, dried, and cracked by such means. Neither has such an effect been described.

In tideless seas the fluctuations of level due to storms are important. Where there is an open reach of water, however, the waves which develop upon its surface break off-shore at a depth which the writer has seen stated somewhere as half the height of the wave below the trough of the same. This action maintains an open sea and an effective working depth, since the waves as soon as they drag on the bottom scour it out and carry the material partly on to the beach, partly into deeper water. In order, then, that any appreciable stretch of bottom normally covered by water should be laid bare, the change of water level between the on-shore and off-shore storms would have to equal at least the height of the waves of the on-shore storms.

As an instance of changes of level under favorable circumstances may be mentioned those of Lake Erie, a narrow body of fresh water 245 miles long lying in a northeast and southwest direction and therefore subject to heavy gales blowing the length of the lake from both directions. As a result Whittlesey has noted a change of level at Buffalo of $15\frac{1}{2}$ feet between flood water and low water.[1] At intermediate points such as Erie and Cleveland there is naturally

[1] Dana, *Manual of Geology*, p. 202.

but little change of level. Even at the points of extreme change a lowering of eight feet below the normal level lays bare but a narrow margin, insignificant in comparison with the total area of this relatively shallow lake. In addition it is observed that such extreme conditions are never of long continuance. Therefore, until instances are cited to the contrary, it must be considered that in all bodies of open water the normal wave action maintains such a depth that off-shore gales cannot lay bare any broad tracts of bottom. Partly land-locked lagoons may in such cases run dry, but such can only form a broader fringe within the actual limits of the land. The border flood zone of tideless seas is therefore not so much due to off-shore winds as to those which blow on-shore. Such may occasionally flood wide belts of lowland, as is seen to take place around the shores of the Gulf of Mexico. By such means in tideless seas mud-cracks may originate above the normal level of the water and therefore upon the land surface, but not to any appreciable extent below the line of mean water.

In the case of the Mississippi the possibilities for the formation of mud-cracks are doubtless somewhat increased by the presence of the mud lumps described by Hilgard, convex or low conical elevations, sometimes 100 feet or more in diameter, showing their tops at the surface. These occur in the shallow waters within one to three miles of the main channel at the mouth of the Mississippi River. They originate in upheavals of the soft but tough bottom. Once formed they discharge mud from the top, the successive layers being but a fraction of an inch thick.[1] These appear to be exceptional phenomena, however, and could hardly be appealed to to account for the structure of extensively mud-cracked formations.

Returning to the consideration of seas with notable tidal ranges it is doubtful if under any climatic conditions mud-cracks could be made upon surfaces left bare by the tides for less than thirty-six hours; but as offshore winds may succeed for a couple of days or more in preventing flooding above the line of neap-flood tide, that may be taken as the limit below which mud-cracks cannot form. Taking the relative heights of the neap and spring tides above the mid-tide line as 4 to 7, this gives 21.5 per cent. or approximately

[1] J. D. Dana, *Manual of Geology* (1895), p. 197.

the upper fifth of the littoral zone as the greatest possible limit over which mud-cracks may form. The upper fifth in level may, however, comprise much more than a fifth of the area, since the salt marshes are especially developed near this level. This indicates that the more favorable places for the development of mud-cracks are either those comprising extensive salt marshes, or regions of unusually great tidal range. As an example of the latter may be cited the Bay of Fundy as pointed out by Lyell.[1]

> On the borders of even the smallest estuaries communicating with the bay, in which the tides rise sixty feet and upwards, large areas are laid dry for nearly a fortnight between the spring and neap tides, and the mud is then baked in summer by a hot sun, so that it solidifies and becomes traversed by cracks, caused by shrinkage. Portions of the hardened mud may then be taken up and removed without injury. . . . . When a shower of rain falls, the highest portion of the mud-covered flat is usually too hard to receive any impressions; while that recently uncovered by the tide near the water's edge is too soft. Between these areas a zone occurs, almost as smooth and even as a looking-glass, on which every drop forms a cavity of circular or oval form, and, if the shower be transient, these pits retain their shape permanently, being dried by the sun, and being then too firm to be effaced by the action of the succeeding tide, which deposits upon them a layer of new mud.

In connection with fossil rain-prints this calls attention to another factor in the problem of fossil foot-prints and rain-prints, structures often associated with mud-cracks, and that is the necessity of drying and hardening before the next invasion of waters which would otherwise wash out the newly made record.

Not wishing to draw an artificial distinction, however, as mud-cracks belonging to the littoral zone may be here included those made from tides of abnormal rise, especially where the water is driven upward by powerful storms. But where flooding of erosion slopes takes place the mud deposited will be ultimately washed away. Where flooding of a river flood-plain takes place, the sea temporarily invades a region which is periodically flooded by fresh water, and therefore mud-cracks in such regions are not distinctive marks of the occupancy of the sea.

It is seen then that exceptionally high tides are not important as necessary conditions for the making of mud-cracks.

[1] "On Recent and Fossil Rains," *Quarterly Journal Geological Society*, Vol. VII (1851), p. 239

As a final exception may be noted the effect of the previously mentioned monsoon winds, as seen on the Runn of Cutch, southeast of the delta of the Indus. In this case winds blowing steadily on-shore for months at a time raise the sea-level sufficiently to flood with sea-water large tracts of marshy country which during another portion of the year become an arid desert. Such conditions are, however, very exceptional and probably are most likely to occur broadly where rivers have previously built up alluvial plains, so that this seasonal extension of the littoral zone may only take place in connection with the continental deposits of rivers.

As the season of off-shore monsoon winds, during which the mud-cracks form, should be normally a season of aridity, it is likely that saline deposits from evaporated sea-water should frequently be associated with the mud-cracks. This is notably the case in the Runn of Cutch. The two features are also associated in the saline beds of New York. If the climate on the contrary is a pluvial one, the rain which would wash off the residual sea-water would also prevent the formation of mud-cracks from the sea-water *as a cause*.

To sum up: it is seen that mud-cracks are confined to an upper fraction of the littoral zone, and where occasionally formed beyond it by inundations of the sea only attain a broad development at the present time in arid regions where continental river deposits have been previously built. In this case the mud-cracked strata should be at least frequently saliferous.

Nature of the geological record.—The nature of the geological record and the features which distinguish mud-cracks of the littoral zone from those made under other conditions may be gathered from the preceding discussion of the conditions of present occurrence. The zone itself marks the transition between a subaërial and a sub-aqueous surface, in the case of deltas each nearly horizontal but at different levels. When the delta deposits of these three regions are seen in cross-section, the littoral will be a transition belt between continental and marine deposits. As the seashore during the accumulation of the strata was ordinarily a shifting line, as seen in cross-section, it will pass nearly horizontally between the two. If the subsiding land was receiving no river deposits, the lower surface will be an erosive surface represented by an unconformity. If the land

surface had been one of river building it may underlie or overlie the littoral and marine deposits according as to whether the delta was retreating owing to subsidence or advancing owing to river building. But in either case the physical conditions of accumulation are so different upon the land and beneath the shallow sea that there is to be expected a marked contrast in the character of the contiguous continental and marine deposits.

Not only will the littoral zone be narrow and transitional in nature compared with the regions which border it on either side, but, as shown in the preceding article, its deposits are liable to suffer much destruction from the planing effect of the waves in the case of a subsiding land and are the first to suffer from subaërial erosion upon an emerging land. Only in the case of a delta building forth into a sea is there a good chance for the preserval of the littoral record. It has been further seen that mud-cracks are not a characteristic feature of the littoral, but can only originate upon its upper fifth or tenth, and in the places most favorable for ultimate preservation there is a grading into the land surface of the delta of which in arid climates the mud-cracks are more characteristic than of the littoral.

From these considerations it is seen that mud-cracks of littoral origin cannot be a characteristic or important feature of geological formations. They are by no means excluded as of occasional occurrence, but it would seem safe, where certain formations are dominated and widely characterized by mud-cracked shaly layers, to assign them to another origin and most probably to one upon a river plain receiving fluvial deposits.

To speak more particularly of the features which will be associated with the occasional mud-cracks of littoral origin may be noted the presence of beach structures of associated sands and muds, frequently fossils characteristic of the littoral zone, leaves and other débris from the land, rain-prints and the foot-prints of such land animals as frequent the shore. These will ordinarily be restricted to animals which seek food native to the littoral or cast up by the sea, as for instance the grubbing of swine for clams upon exposed mud flats, or birds which run over the flats and beaches for annelids or other small organisms.

The mud-cracks should be most frequently developed upon

coasts where the tides are high, and in this case the areas of salt marsh should be rather frequently cut up by wide and deep tidal channels filled with coarser material. Yet in most mud-cracked formations such erosion of deep channels across the mud-cracked layers is conspicuously absent.

Under the subject of mud-cracks of fluvial plains the subject of variegated shales was discussed and it was concluded that in those formed under a subarid climate the conditions were especially favorable for their production. Before closing the present topic, therefore, the subject should be again mentioned, in order to find if they may not form equally readily in the littoral zone or even in estuarine or open sea portions of the zone of marine deposits. Along the littoral somewhat the same conditions of variable exposure to the air exist as upon flood plains. Below the line of low tide, however, extensive tracts are never exposed to the air except by broad changes of level, and local variations in the amount of organic matter present, to which variegated shales are presumed to chiefly owe their origin, will depend upon conditions of current and influx of sediment. Variegated colors should therefore be associated more markedly with variations of texture and composition than is necessarily the case with the deposits upon flood plains; changes more analogous with the contrast between channel sands and true flood-plain muds.

That red muds as well as blue muds of the terrigenous zone may form on ocean bottoms is indicated by the red muds chiefly found off the Brazilian coast. "Its red color is thought to be due to the great amount of hydrous peroxide of iron brought to the sea by the rivers and which cannot be reduced by organic matter, as in the case of the blue mud. The area covered by it is, however, small, and is estimated at about 100,000 square miles,"[1] while the blue muds cover some 14,000,000 square miles.

Variegated shales may therefore originate in any zone of sedimentation and under any depth of water, but those of marine origin are due to broad and slow changes upon the land and should not show any of the local variations and partial independence between color and stratification which may mark the deposits of a flood plain. Within limits variegated shales may be considered, therefore, as rather characteristic of continental and littoral deposition.

[1] W. B. Clark, *Geological Survey of New Jersey, Annual Report*, 1892, p. 223.

CONCLUSIONS ON GEOLOGICAL SIGNIFICANCE OF MUD-CRACKS

From the preceding analysis of the origin of mud-cracks, as observed at the present time and the conditions under which they would be geologically preserved, it would seem that next to coal beds formed *in situ*, or abundance of land fossils belonging to the animal kingdom, that mud-cracks form one of the surest indications of the continental origin of argillaceous deposits. The structure is also seen most commonly to originate under climatic conditions where the other tests are apt to fail.

It may be considered, therefore, that mud-cracked shales predominantly indicate former flood-plain deposits, usually on delta surfaces which have displaced shallow seas. Removed from the vicinity of the sea and occurring in continental basins with older rock rims, they may have originated as playa deposits and indicate a formerly truly desert climate.

More rarely mud-cracked shales may be found as transitional belts separating unlike formations and indicative of the sun dried margins of former lakes or seas. In any case the associated characteristics which have been pointed out should assist in arriving at a conclusion in regard to the particular conditions of origin.

PREVAILING INTERPRETATIONS

The prevailing views upon a subject are exemplified by the statements of the current textbooks and manuals. These not only guide the formation of views of the younger students of the subject, but represent the longer-established and verified opinions of the older body of scientists. While frequently specialists in various lines would regard the presentation of their departments even in the better textbooks as not strictly up to date, this is, on the whole, not without its benefits, since it is necessary for new knowledge to become seasoned with time before its exact place and importance can be assigned among the body of well-established principles.

It will be desirable in summing up the present subject to compare the conclusions just arrived at with those statements concerning the significance of mud-cracks which are given in the standard texts, and which it is believed have been largely influenced by the habit

of interpreting all sediments as marine unless there was positive evidence to the contrary. It is in no spirit of adverse criticism that this is done, but in order to call sharper attention to the degree of variance with the present conclusions and the desirability of confirming or modifying the latter by further observation and analysis.

Turning first to the work of the best known of American geologists: J. D. Dana, in his *Manual of Geology*[1] stated that mud-cracks are made on drying mud flats, but with customary insight was evidently careful not to restrict them entirely to the seashore, since on the next page he refers to them as well as rain-prints as made by "exposure above the water level at low tide, or at least a low stage of the waters." Thus Dana recognizes the possible continental origin, but places the emphasis, perhaps unconsciously, upon the sea-beach or estuarine origin.

Chamberlin and Salisbury in their *Geology* (1904), Vol. I, p. 466, state that "sediments are sometimes exposed between tides, or under other circumstances, for periods long enough to permit drying and cracking at the surface."

Sir A. Geikie in his *Text Book of Geology*, 4th ed. (1903), pp. 643, 644, speaks of mud-cracks as vestiges of shores of former seas and lakes, and one of the kinds of evidence showing that a locality was sometimes laid bare of water.

James Geikie, in his *Structural and Field Geology* (1905), p. 116, mentions the present occurrence of mud-cracks around the shores of inland seas and lakes, and states that the same action may take place on low flat beaches which are exposed to a hot sun during the retreat of the tide. Although lake shores are mentioned first, no discussion is given as to the relative geological importance of the two situations in producing mud-cracks.

In none of the preceding books is the possibility mentioned of mud-cracks being formed over flood-plains of rivers and apart from permanent bodies of standing water. Yet these authors are authorities upon the subject of sedimentation and sedimentary structures, and in Sir A. Geikie's *Text Book* especially, an appreciation is constantly shown of the importance of fluviatile formations. It remains a question, therefore, if this difference of view upon the significance

[1] P. 94; see also pp. 742, 745 (1895).

of mud-cracks is due to an inheritance of expression from the past or if undue importance has been given in the present paper to mud-cracks of continental, and especially of flood-plain, origin in arid and subarid climates.

In both LeConte's and Scott's textbooks no mention is made of mud-cracks originating by any other means save by the laying-bare of tidal flats, and in both it is used as an argument proving the estuarine nature of the Newark basins; and Scott discusses the question whether the basins were parts of one or two "continuous bodies of water," p. 445.

Recently Huntingdon[1] has spoken of sun-cracks and ripple-marks taken in connection with other features as initiating continental sedimentation of the Tertiary in Central Turkestan.

> It appears as though, after the retirement of the sea, the land was covered with great playas, on which water first stood in thin sheets, forming ripple-marks in the mud and then retired or was evaporated, allowing the surface to become sun-cracked. As time went on streams began to flow across the playas, at first slow and broad and able to cut only shallow channels which were afterward filled and covered, assuming the form of very thin lenses of a material slightly different from that of the surrounding playa strata. Then, as the strength of the streams increased, sand was deposited over the whole area, and the channels, now deep and distinct, were filled with gravel. Lastly gravel was deposited almost everywhere.

So far as the writer is aware the only attempt at a discussion of the several methods of origin of mud-cracks and the relative chances of their preserval is by Penck,[2] who points out that they, as well as foot-prints and rain-prints, occur on sea-beaches, over the flood-plains of rivers and the shores of interior seas, but that the surface bearing the markings must to a certain degree have hardened and consequently have remained as a land surface for a certain length of time in order that the impressions should not be washed out by the next invasion of waters. For that to be accomplished he states that the sea-coast is less favorable than the flood-plains of rivers and the margins of lakes. In the latter cases the exposed floor dries for weeks or months and attains a considerable hardness before being again overflowed.

[1] "Explorations in Turkestan," *Carnegie Institution of Washington* (1905), pp. 164, 165.

[2] *Morphologie der Erdoberfläche* (1894), Vol. II, pp. 25, 26.

ILLUSTRATIVE GEOLOGICAL APPLICATIONS

In the preceding paper under the heading of "The Relations of Continental and Marine Sedimentation through Geological Time," it was concluded, not from a detailed study of the strata, but entirely from the broader relations at present prevailing, that at certain times in the past continental sedimentation should have played an important rôle, especially in the form of fluviatile deposits filling interior basins or displacing epicontinental seas. Having made this present examination of the different methods by which mud-cracks may originate, together with some of their associated characteristics, it will be well to apply it as a test to the conclusions of the preceding paper. If the result is a confirmation, there will thus be two largely independent lines of reasoning which arrive at the same result; a result in which therefore correspondingly more confidence may be placed.

MUD-CRACKED FORMATIONS OF THE PRE-CAMBRIAN

In both northwestern Montana and northwestern Arizona occur a series of predominantly arenaceous and argillaceous formations of great thickness which are distinctly older than the Middle Cambrian, since these lower formations were gently folded and base-leveled before the transgression of the Middle Cambrian sea. Yet these terranes are remarkably free from metamorphism and still retain their original characters. For this reason they are selected for illustration and briefly described. It was suggested in the preceding article that on account of the general nature of the deposits and the fact that the early Cambrian as well as the immediately pre-Cambrian were periods of great continental extension, the hypothesis of subaërial and fluviatile origin for certain formations should be at least entertained until disproved. It is now proposed to describe certain features of these formations in detail in order to arrive at some conclusion in regard to their continental, littoral, or marine origin, the conclusions being drawn after the presentation of the details.

PRE-CAMBRIAN FORMATIONS OF MONTANA

These are described by Walcott under the title of the "Belt Terrane"[1] and by Willis as the "Algonkian of the Lewis and Liv-

[1] Pre-Cambrian Fossiliferous Formations," *Bulletin Geological Society of America*, Vol. X, pp. 201, 215.

ingston ranges."[1] The two districts described above are about 150 miles apart in a general north-northwest and south-southeast direction; and as the intermediate region has not been studied in detail, Willis does not pretend to correlate closely the several formations described by him in the northwest with those described by Walcott from the district near Helena, but the similarity of sequence is sufficiently striking to warrant placing them in juxtaposition as is done below.

Belt Formation, Helena Region—Walcott	Thickness in feet	Algonkian of Northwest Montana, Lewis and Livingston Ranges—Willis	Thickness in feet
Marsh shales	300	Kintla argillite / Sheppard Quartzite	800+ / 700±
Helena limestone	2,400	Siyeh limestone	4,000
Empire shales	600		
Spokane shales	1,500	Grinnell argillite	1,000 to 1,800
Greyson shales	3,000	Appekunny argillite	2,000+
Newland limestone	2,000	Altyn limestone	1,400+
Chamberlain shales	1,500	(Bottom of limestone not exposed)	
Neihart quartzites and sandstone	700		
	12,000		9,900 to 10,700

Brief descriptions of these formations are quoted as follows, those of the equivalent formations of the two localities being placed together:

Neihart quartzite and sandstone Helena region, Little Belt Mountains.—In this formation are included the reddish, coarse sandstones, with interbedded dark greenish layers of fine-grained sandstone and shale, beneath the Chamberlain shales. The lower 400 feet of the formation is a massive, sometimes cross-bedded quartzite, which, in some of its members, where unaltered, is a compact, hard sandstone. The prevailing color is pinkish-gray on the freshly exposed surface, with dark and iron-stained weathered surface. Occasional layers of a fine conglomerate occur in some portions near the contact with the gneiss.[2]

About 300 feet above the base the character of the formation changes. The pink and white pure quartzites are replaced by more thinly bedded rocks, no longer of pure arenaceous material, but containing an admixture of greenish mica, which higher in the group forms the layers of mica shales interbedded with the quartzite. The higher strata are still more impure and the quartzite beds are but six to twelve inches thick, blackened by carbonaceous material that now forms a prominent feature of the intervening shales, becoming increasingly abundant until the latter rocks are true black shales in which the green mica no

[1] "Stratigraphy and Structure, Lewis and Livingston Ranges, Montana," *ibid.*, Vol. XIII, pp. 316–24.

[2] *Bulletin Geological Society of America*, Vol. X, p. 204.

longer shows. At the same time the quartzite beds decrease in thickness and purity, while the interbedded shale increases in thickness and purity, so that an arbitrary line must be drawn separating the two formations.[1]

Chamberlain shales, Helena region, Little Belt Mountains.—This formation is composed of a series of dark silicious and in places arenaceous shales. Ripple-marks, mud-flows, and sun-cracks were occasionally seen, but no traces of life were observed. The dark shales frequently form low cliffs along the canyon side, near the beds of the streams.[2]

Newland limestone, Helena region, Little Belt Mountains.—At the typical locality on Newland Creek the limestones are thin bedded, the layers averaging from two to six inches, with shaly partings of variable thickness between them. In the section of Sawmill Canyon, near Neihart, the layers are somewhat thicker, more impure, and with a greater number of beds of interbedded shale. The prevailing color of the limestone is dark bluish-gray on fresh fracture, and buff to straw color on the weathered surface.[3]

Altyn limestone, Lewis and Livingston Ranges.—Limestone, of which two members are distinguished; an upper member of argillaceous, ferruginous limestone, yellow, terra-cotta, brown, and garnet-red, very thin-bedded; thickness about 600 feet; . . . . and a lower member of massive limestone, grayish-blue, heavy-bedded, somewhat silicious, with many flattened concretions, rarely but definitely fossiliferous; thickness, about 800 feet.[4]

Greyson shales, Helena region, Little Belt Mountains.—Dark-colored, coarse, silicious, and arenaceous shales, passing above into bluish-gray, almost fissile shale, which, when broken up, weather to a light gray fissile shale, resembling a poor quality of porcelain. These in turn are succeeded by dark gray silicious and arenaceous shales, with interbedded bands of buff-colored sandy shales and occasional layers of hard, compact, greenish-gray and drab silicious rock. At the base of this series, in Deep Creek Canyon, a belt of quartzites occurs, interbedded with shales, the base of the quartzites showing ten feet of interformational conglomerates, composed of sand and pebbles up to eight inches in diameter, and derived from the subjacent Belt rocks.[5]

Appekunny argillite Lewis and Livingston Ranges.—The Appekunny argillite is a mass of highly silicious, argillaceous sediment approximately 2,000 feet in thickness. Being in general of a dark gray color, it is very distinct between the yellow limestones below and the red argillites above. The mass is very thin bedded, the layers varying from a quarter of an inch to two feet in thickness. Variation is frequent from greenish-black argillaceous beds to those which are reddish and whitish. There are several definite horizons of whitish quartzite from fifteen to twenty feet thick. The strata are frequently ripple-marked, and occasionally coarse grained, but nowhere conglomeratic.[6]

[1] W. H. Weed, *Geology of the Little Belt Mountains*, pp. 281, 282.

[2] *Bulletin Geological Society of America*, Vol. X, p. 206.

[3] *Ibid.* [4] *Ibid.*, Vol. XIII, p. 317. [5] *Ibid.*, Vol. X, p. 206.

[6] *Ibid.*, Vol. XIII, p. 322.

Spokane shales, Helena region, fifteen miles east of Helena.—The Spokane shales occur as massive beds of silicious and arenaceous shales of a deep red color. The arenaceous shaly portions frequently thicken up into thin layers of sandstone. The shales break down on exposure, but they are usually sufficiently firm to resist erosion and form strongly marked slopes and cliffs.[1]

The present writer had an opportunity in 1901 of examining the Spokane about 20 miles northwest of Helena and found the shaly layers frequently mud-cracked.

Grinnell argellite, Lewis and Livingston Ranges.—A mass of red rocks of predominantly shaly argillaceous character is termed the Grinnell argillite from its characteristic occurrence with a thickness of about 1,800 feet in Mount Grinnell. These beds are generally ripple-marked, exhibit mud-cracks and the irregular surfaces of shallow water deposits. They appear to vary considerably in thickness, the maximum measurement having been obtained in the typical locality, while elsewhere to the north and northwest not more than 1,000 feet were found. It is possible that more detailed stratigraphic study may develop the fact that the Grinnell and Appeknuny argillites are really phases of one great formation, and that the line of distinction between them is one diagonal to the stratification. The physical characters of the rocks closely resemble those of the Chemung and Catskill of New York, and it is desirable initially to recognize the possibility of their having similar interrelations.[2]

Empire shales, Helena region, twenty miles northwest of Helena.—These are greenish-gray massively bedded, banded, silicious shales.

Helena limestone, Helena region, Helena.—The Helena limestone formation is composed of more or less impure bluish-gray and gray limestone, in thick layers, which weathers to a buff and in many places to a light gray color. Irregular bands of broken oölitic and concretionary limestone occur at various horizons. Bands of dark and gray silicious shale and greenish and purplish argillaceous shale are interbedded in the limestones. These bands are from half an inch to several feet in thickness. There are also beds of thinner bedded limestones, especially toward the top of the formation.[3]

Siyeh limestone, Lewis and Livingston Ranges.—Next above the Grinnell argillite is a conspicuous formation, the Siyeh limestone, which rests upon the red shales with a sharp plane of distinction, but apparently conformably. The Siyeh is in general an exceedingly massive limestone, heavily bedded in courses two to six feet thick like masonry. . . . . Occasionally it assumes slabby forms and contains argillaceous layers. It is dark blue or grayish, weathering buff, and is so jointed as to develop large rectangular blocks and cliffs of extraordinary height and steepness. Its thickness, as determined in the nearly vertical cliff of mount Siyeh, is about 4,000 feet.[4]

[1] *Bulletin Geological Society of America*, Vol. X, p. 207.

[2] *Ibid.*, Vol. XIII, p. 322.

[3] *Ibid.*, Vol. X, p. 207.

[4] *Ibid.*, Vol. XIII, p. 323.

Sheppard quartzite, Lewis and Livingston Ranges.—A distinctly sandy phase of deposition succeeding the extrusive rhyolitic eruption capping the Siyeh limestone has resulted in a quartzite which is very roughly estimated to have a thickness of 700 feet.[1]

The present writer has observed a basal quartzite to the Marsh shales in a similar stratigraphic relation upon Greenhorn Mountain, sixteen miles northwest of Helena. But the occurrence of the quartzite was lenslike and not persistent for many miles.

Marsh shales, Helena region.—At Helena there is a thickness of about 250 feet of shales and thin-bedded sandstones of the Belt Terrane above the Helena limestone and beneath the Cambrian sandstones. The same bed, on the north side of Mount Helena, is reduced to 75 feet in thickness, but to the northwest the formation increases in thickness to 300 feet or more.[2]

Kintla argillite, Lewis and Livingston Ranges.—Argillite and quartzite, thin-bedded, maroon red, ripple-marked, and sun-cracked, containing casts of salt crystals; also occasional beds of white quartzite and some calcareous; thickness 800 feet; no upper limit seen.[3]

The Kintla formation closely resembles the Grinnell, and represents a recurrence of conditions favorable to deposition of extremely muddy, ferruginous sediment. The presence of casts of salt crystals is apparently significant of aridity, as the red character is of subaërial oxidation. The formation has an observed thickness of 800 feet, but no overlying rocks were found. Its total thickness is not known, and the series remains incomplete.[4]

Discussion.—The very similar general nature of these formations at a distance of 150 miles from each other indicates similar conditions of accumulation over wide areas, though it is possible of course that the stratigraphic cycle was not strictly contemporaneous in the two regions. The volume of material which must have been eroded to supply these sediments was far greater than the volume of the sediments, since the one kind of sediments of any epoch, occurring at *both* localities, represents but a portion and, in the case of the limestones and quartzites, but a small portion, of the rock masses whose erosion supplied the material.

Taking Clarke's figures[5] of the average amounts of the oxides and common minerals in the "primitive crust of the earth" it is seen that an approximately pure dolomite which should contain all of

[1] *Ibid.*, p. 324.

[2] *Ibid.*, Vol. X, p. 207.

[3] *Ibid.*, p. 316.

[4] *Ibid.*, Vol. XIII, p. 324.

[5] "Analysis of Rocks, Laboratory of the U. S. Geological Survey," *Bulletin U. S. Geological Survey No. 168* (1899), pp. 14, 16.

the lime and magnesia of a primitive rock mass would contain but about one-tenth of the original, and in volume, allowing for the carbon dioxide in combination with bases, would roughly represent about a fifth of the original. In this case, however, since the material has been deposited from solution, it does not signify a necessary origin from contiguous land masses.

The average igneous rock, containing, according to Clarke, 10 per cent. of quartz, a pure quartzite will represent less than one-eighth of the original rock mass, but an argillite, containing variable amounts of the original quartz and additional water and carbon dioxide combined with the bases, represents a far higher, but indefinite, proportion of the original rock mass. Quartzites and argillites, however, since they cannot be transported across deep bodies of water imply contiguous land. The great thickness and similarity of the arenaceous and argillaceous formations over a wide area point to an originally still more widely spread character, since there is no indication that these districts were near the original limits. But their volume indicates deep erosion of a correspondingly extensive contiguous land. The formations do not show the local variations and conglomeratic nature which would indicate the erosion of a nearby mountain range, and therefore the denudation must have taken place from a wide area. The similar formations which are known to exist in British Columbia, Utah, Nevada, California, and Arizona emphasize still further the profound erosion of widespread adjacent land masses of late pre-Cambrian time.

Thus a detailed examination of the composition and texture of these Montana formations allows inferences confirming *for this region* the statements made in the previous article from more general grounds concerning the wide development of the continents in the later pre-Cambrian times.

In regard to the topographic and sedimentary cycles expressed by the succession and character of the formations it is seen that the two great limestones represent long-enduring incursions of the sea, while the quartzites and argillites represent the uplift and erosion of neighboring lands of large area.

The Neihart quartzite.—The cleanness and partially deferrized character of the basal formation, the Neihart quartzite, indicates shallow water off-shore deposit, subject to the prolonged sorting

and attrition characteristic of the work of currents and waves or of desert winds resulting in the accumulation of dune sands. The latter idea is perhaps made improbable by the transition into, and alternation with, the deoxidized and carbonaceous lower members of the Chamberlain shales.

The Chamberlain shales grade, on the one hand, into the underlying quartzite and, on the other, into the Newland limestone. These relations, in addition to the dark silicious and occasionally arenaceous character and occasional ripple-marks, suggest a quiet offshore formation. The mud-cracks noted by Walcott may be either of littoral or fluvial origin, but in either case imply a nearby land. The lack of a more arenaceous character may be due, therefore, to a topographic old age and lessened stream gradients of the land, or to the river material having been borne from a great distance.

Newland and Altyn limestones.—The inauguration of the era of the Newland and Altyn limestones may be due as much to the lack of supply of mechanical sediments as to subsidence and incursion of the sea.

Greyson and Appekunny argillites.—Following the limestone came some 2,000 to 3,000 feet of Greyson and Appekunny argillites. The generally dark gray color, thin-bedded lamination, occasional ripple-marks, and quartzitic strata suggest the submarine deposits poured into a sea as a result of the re-elevation of a contiguous land.

The association with the limestone below, the absence of conglomerates and observed mud-cracks, and the contrast in color with the deep-red and mud-cracked formation above all tend to confirm this interpretation.

The Spokane and Grinnell argillites, from 1,000 to 2,000 feet in thickness, on this view represent subaërial delta deposits over a region where sedimentation had gained upon subsidence to such an extent as to fill up and exclude the sea. In contrast to the inferior argillites are to be noted the highly oxidized character indicated by the deep red color, the frequent alternations of sandstone strata, and especially the widespread occurrence of mud-cracks. These are not sparingly present and developed in strata transitional between two distinct types, as would be characteristic of mud-cracks of the littoral zone, but on the contrary are developed in the normal red shales. Furthermore, the exposed sections show throughout a

marked sameness in color and a similar repetition of argillaceous and arenaceous beds. The areal extent, the fineness and evenness of grain, combined with the evidences of aridity, bespeak an extensive delta fan, comparable in size and climatic environment to those of certain of the larger Asiatic rivers of the present time.

The lack of knowledge as to the extent and relations of the formation will not allow of a closer comparison, but it is seen that it represents the continental culmination of the sedimentary cycle as the preceding Newland and Altyn limestones represented the opposite or marine phase.

The cycle appears to be less dependent here upon a mere transgression and recession of the sea as the active agent, than upon the wasting-away and the rejuvenation of adjacent land masses, which, upon being re-elevated, supply such a flood of sediment as to crowd back and dispossess the sea, the subsidence of the geosyncline going forward more or less continuously but at a variable rate.

The succeeding formations of this terrane indicate a repetition of this cycle, the Empire shales, showing greens and grays and passing into the upper limestones, doubtless represent the submarine deposits made during the transgression of the sea across the subsiding former delta surface. Then followed several thousand feet of limestone formation. This is largely thin bedded and shaly in the upper portions in the Helena region and various features described elsewhere suggest that it was largely accumulated in a shallow sea. This limestone was succeeded in places by quartzites which suggest wave-sorted deposits, and finally by a deep red mud-cracked series of argillites, somewhat similar to the Spokane-Grinnell formation, suggestive once more of land deposition under conditions of aridity. The thickness of this formation varies widely, the upper surface being a base-level erosion surface upon which is superimposed the Middle Cambrian marine transgression across a far-reaching and topographically ancient land.

THE GRAND CANYON SERIES OF ARIZONA

Leaving the preceding region and passing to the Grand Canyon of Arizona, some 750 miles south of Helena and some 950 miles south of the international boundary, a different series of rocks is

found to occur, but one holding a similar stratigraphic position, being embraced between the metamorphic formations of the Vishnu and Archean below and the unconformable Middle-Cambrian above. Walcott gives the series a total thickness of 11,950 feet, divided into two terranes, the upper or Chuar containing 5,120 feet of strata of which 285 feet are limestones and 4,835 feet brown to black or variegated shales and some reddish-brown sandstones. The lower or Unkar terrane attains a total thickness of 6,830 feet of which from 110 to 210 feet are limestones and the balance brown to vermilion sandstones and shaly sandstones with a basal conglomerate 30 feet in thickness. The Unkar is characterized by a great thickness of reddish-brown sandstones. The detailed section of the Unkar as given by Walcott follows, the italics being introduced:[1]

SECTION FROM THE SUMMIT DOWNWARD	FEET
1. *a*) Massive bed of gray to reddish magnesian limestone, passing below into a calciferous sand rock	50–150
b) Light gray, shaly sandstone	25
c) Irregular, massive beds of yellowish-brown sandstone	50
d) Partially crossbedded, fine grained, purplish-brown sandstone.	50
e) Reddish-brown sandstone and sandy shales, ripple-marked.	200
	475
2. Lava beds:	
a) Nine lava flows aggregating	770
b) Interbedded sandstones	30
At Chuar lava hill the lava beds are 1,000 feet thick.	800
3. Sandstones (upper)	
a) Shaly, vermilion, rather fine-grained sandstones, with intercalated bands of greenish-gray, followed below by 700 feet of vermilion beds of a uniform character, and massive beds with arenaceous, shaly partings, the massive beds breaking up into shale and sandstone on the talus slopes. *Ripple-marks and shrinkage cracks characterize the upper, shaly beds*	1730
b) The vermilion sandstones of *a*) pass into chocolate colored sandstones, that for 125 feet down unite in the general slope of the beds above. Below, a cliff is formed of five massive bands of chocolate-colored, slightly micaceous sandstone, separated by shaly sandstone partings of a greenish color below and a chocolate color above	925
c) Reddish-brown to chocolate, more or less shaly sandstone, 125 feet, underlain by 300 feet of friable sandstone and arenaceous and micaceous shale	425
d) Irregularly bedded, compact sandstone:	
Curiously twisted and gnarled layers	15
Massive, grayish layer	10
Light gray layer with reddish spots, friable, shaly in places	125
	3230

[1] "Pre-Cambrian Igneous Rocks of the Unkar Terrane," *Fourteenth Annual Report* (1894) U. S. Geological Survey, Part II, pp. 510–12.

4.	Sandstones (lower):	
	a) Compact, quartzitic, gray sand rock, 25 feet, with 65 feet of hard, compact sandstone	90
	b) Massive, compact, cliff-forming, brown, buff, and purplish-brown sandstone	1200
	c) 1. Reddish-brown to vermilion, friable, shaly sandstone	200
	2. Brick-red, shaly sandstone	250
	3. *Brown, friable, shaly sandstone, ripple-marks and shrinkage cracks*	300
	4. Same in more massive layers, with fine, siliceous conglomerate (10 feet) at the base	80
		80
		2120
5.	*a*) Light gray limestone with interbedded laminæ of quartzitic shale	8
	b) Brown sandstone with a bed of silicious conglomerate, 2 feet	30
	c) Reddish cherty limestone	10
	d) Reddish-brown limestone	2
	e) Dark, reddish-brown slate	5
	f) Light gray, compact shaly limestone	14
		69
6.	Dark, compact basaltic lava in one massive flow	80
7.	Light gray, compact shaly limestone with pinkish tinge between the laminæ; it is a little cherty near the base, or with thin, hard, interbedded layers of sandstone	26
8.	Silicious conglomerate formed largely of pebbles derived from the upturned edges of the pre-Unkar strata, upon which it rests unconformably	30
	Total thickness of the Unkar terrane	6830

Discussion.—The basal silicious conglomerate derived from the upturned edges of the underlying beds and followed by 175 feet of limestones containing a lava bed and some sandstone may be taken as a good indication of the invasion and continued presence of the sea.

It is noticed, however, that beginning 205 feet above the base are 10 feet of a fine silicious conglomerate which suggests a possible origin as a wave-sorted beach sand. Above this follows 370 feet of brown, friable, shaly sandstones showing ripple-marks and shrinkage cracks. These could be explained as of littoral origin by supposing that the subsidence and sedimentation remained exactly balanced so that this zone was the transition between the subaërial and submarine portions of a delta during the entire time of the deposit of the 370 feet. Even assuming a littoral origin, however, the immediate vicinity of a shore is implied and it seems a much simpler hypothesis to suppose that the mud-cracks were of flood-plain origin. Under this assumption the cracks could be more readily accounted for and it is not necessary to postulate an exact balance between the

subsidence, the marine planation and the delta building during all the time of accumulation, it being only necessary to assume that sedimentation remained in excess of subsidence and that the shore was a fluctuating line, of which this locality was continually on the landward side. These mud-cracked strata form the basal portion of the lower sandstones. Above them are 1,650 feet of red buff, brown, and vermilion sandstones and shaly sandstones similar in character, but not noted by Walcott as characterized by mud-cracks. The similar characters and especially the color of the iron oxide implying complete subaërial oxidation either before or after deposition suggest a continuance of the continental conditions. If deposited beneath the sea it would be expected that the continued wave action which affects the sandy deposits of shallow seas would, at least, in part, have separated the clay and iron from the grains of sand, producing cleaner gray quartzitic layers. Such a change is, in fact, noted in the compact, quartzitic, gray sand rock which separates the lower from the upper sandstone of the Unkar.

The question arises as to why the mud-cracks should be absent from the 1,650 feet of lower sandstones, if the latter were really of subaërial origin. The answer is that, even if the necessary periods of desiccation were present between the river inundations, mud-cracks need not necessarily arise. A sandy nature is unfavorable for their development, and the strata are much more sandy, on the whole, than in the case of the Spokane and Marsh shales of the Belt terrane. Again, a canyon wall is not a favorable place upon which to observe the bedding surfaces of gently dipping strata. It is furthermore possible that mud-cracked strata which could be observed by careful search were not noted, since Walcott was not conducting the examination with that end in view as a principal object. Finally mud-cracks which were noted were not always recorded in this necessarily brief synopsis of the strata, at least if they were off the line of the section, since on p. 515 of the article cited it is stated that at Chuar Lava Butte numerous ripple-marks and mud-cracks occur among the sandstones and shales covering the uppermost lava flow, yet mud-cracks at this horizon are not mentioned in the synopsis which has been given.

Returning to the description of the Unkar stratigraphic section,

the upper sandstones below the lava beds comprise 3,230 feet, nearly all being again vermilion, reddish-brown, or chocolate in color. Occasional partings of a greenish-gray are noted, and the upper shaly beds are characterized by ripple-marks and shrinkage cracks. It would seem from this that if the gray quartzite separating the upper and lower sandstones is, indeed, a beach and marine deposit, that the transgression was but temporary, the beach was pushed back and subaërial deposition continued.

Following this stage occurred a series of outpourings of lava, thin layers of sandstone separating most of the flows. The lava beds aggregate from 770 to 1,000 feet in thickness, varying this much in a distance of about four miles. The partings of shale and sandstone are widely distributed and of uniform thickness over considerable areas (p. 517) and on Chuar Lava Butte it is noted that the upper lava flow is capped by 35 feet of cholocate-brown sandstone and sandy shales with numerous ripple-marks and mud-cracks occurring among the layers (p. 515).

A study of the relations of the traps and interbedded sandstones with respect to the alternative hypotheses of marine or continental origin would probably offer some evidence in support of one view as against the other. The widespread character of the lava flows indicates that they were poured out over a level surface. The subaërial portion of a delta with a slope of normally not more than a foot per mile is more broadly level than the submerged portion, but, on the other hand, is also more cut by stream channels.

The more or less viscous nature of lava would cause the upper surface of the flows to depart from a true plane. If above the sea level the streams would tend to erode the upper surface to some extent and result in thicker deposits of sand and clays in the hollows of the upper surface, leveling it once more to grade. These effects might be less marked if the lava flows were poured out beneath the sea.

In the absence of field study with these points in view it seems best to leave the problem as an open question, but the mud-cracked layers covering the upper lava flow indicate rather strongly the subaërial origin of at least that particular sheet.

Above the last lava flow are found 250 feet of these apparently

land-deposited beds followed by 50 feet of irregular massive beds of yellowish-brown sandstone and 25 feet of light gray shaly sandstone. These by their contrast in color presumably represent the off-shore deposits of a transgressing sea and are followed by 50 to 150 feet of massive, gray to reddish magnesian limestone, closing the deposits of the Unkar terrane.

The detailed section of the following Chuar terrane is not quoted in full as the beds are not described by Walcott as mud-cracked, nor do most of them by their other characters strongly suggest subaërial deposition. As previously noted, they embrace 5,120 feet of strata of which 285 feet are limestones. The greater portion of the balance consists of brown to black, gray, or variegated shales, with some reddish-brown sandstones, often shaly. Deposition in off-shore waters beyond the reach of beach action is suggested as the mode of origin of much of the formation by the prevailing difference in color, the more shaly character, and the beds of limestone scattered at intervals through the entire terrane. Occasional transitions to shore deposits of an arid climate are similarly suggested by the variegated shales, and especially masses of white and pink gypsum found in a few localities in one horizon which consists of black argillaceous shale with chocolate and greenish, sandy and argillaceous shales beneath, carrying hard layers of sandstones.

A classification of the Chuar section into appreciably calcareous and arenaceous portions suggests three movements of subsidence with invasions of the sea and four periods of halting or possibly elevation with approach of the littoral to this region, the series ending with 125 feet of massive, reddish-brown sandstone, with irregular layers of similar color and containing numerous fragments of sandstone-shale of lighter color.

The thorough and accurate observations of Walcott have made it possible to give this discussion of continental as opposed to marine origin both for the Belt and Grand Canyon series, although the problem of a possible continental origin is not discussed in the original papers and possibly was not seriously in mind, since such a question had never been raised in regard to them. Since the facts have been freely quoted, however, it is also desirable to give the observer's interpretation, which is throughout that of a marine

origin. In regard to the upper lavas of the Unkar terrane Walcott states:

> The first coulée flowed over the level ocean bed, in which 5,000 feet of sediment, that now forms a reddish-brown sandstone, had accumulated on the upturned and eroded edges of the Archean, the few layers of limestone and the one flow of lava, 150 feet in thickness near the base scarcely serving to break the great sandstone series.[1]

Again the author states that

> The wide distribution of thin layers of sandstone, shale, etc., of uniform thickness over considerable areas indicates a relatively smooth sea bed at the time of the spreading of the first sheet of (the upper) lava over it; and that the sea was shallow, is shown by ripple-marks and the filling of sun-cracks.[2]

CONCLUSION ON THE NATURE OF THE PRE-CAMBRIAN SEDIMENTATION

In the absence of personal observation with the particular problem in mind any other interpretation than that given by Walcott should be held with reservation, but it has been shown that in view of the highly oxidized character of the sandstones of the Unkar terrane, and mud-cracks frequently found in the shaly beds, that the presumption is in favor of a continental origin and the burden of proof is rather upon those who would give the marine interpretation.

The discussion of these pre-Cambrian deposits but especially of the Montana occurrences, shows how completely in accord is the hypothesis of the dominant flood-plain origin of mud-cracks with the other marks of subaërial deposition in an arid climate. The mud-cracks are confined to just such formations as from other characteristics suggest a flood-plain origin and these formations are usually separated from the deposits of limestone by transitional formations which differ in color, in character, and in the absence of mud-cracks, suggesting the true submarine deposits originating between the shore and the open sea.

Assuming that a strong case has been made out for the continental origin of certain of these pre-Cambrian formations, it is seen that in the two regions examined the conclusion is justified which was reached from general considerations in the preceding paper—that the late pre-Cambrian being an aeon of wide continental extension should show in its epicontinental deposits a considerable proportion

[1] P. 504. [2] P. 517.

of subaërial origin. The two regions are unusually favorable for study in this particular, since, as previously noted, the deposits have been relatively little disturbed by later earth movements and the original sedimentary record has not been obliterated through the processes of metamorphism.

A general conclusion should be founded on a far wider study of occurrences, but such would run beyond the limits of this paper. It may be noted in passing, however, that the Montana region shows an unusual proportion of carbonate rocks, while the pre-Cambrian deposits over the world as a whole apparently are characterized by minor amounts of carbonates, rocks whose presence in notable proportions are usually the surest indication of truly marine conditions. Such a poverty in limestones may in a small measure be accounted for by a possible dominance of disintegration over decomposition in the erosion of those times, the lime thus in part not being set free and the disintegrated products giving rise upon metamorphism to a large proportion of gneisses, graywackes, and feldspathic schists, instead of quartzites, argillites and marbles.

Highly silicious rocks are, however, not uncommon, and the question arises as to where the corresponding quantities of salt, gypsum, and dolomitic limestones are to be found. In the long time elapsing since their origin these might have been completely leached out by subterranean waters, as Rutley has shown,[1] if they had remained near the surface in the zone of circulating waters. But the pre-Cambrian rocks are usually highly metamorphic and have been buried deeply in the zone of anamorphism during a considerable proportion of their existence, so that such an explanation can hardly apply to them in very much greater measure than to the Eopaleozoic limestones which remain in such abundance.

The bulk of the salt is doubtless still in solution in the sea and is a measure of the volume of erosion in those early ages in addition to that of later times. The corresponding dolomites, however, since they are apparently not found in proportionate abundance upon the continents must presumably repose within the limits of the present ocean basins.

[1] "On the Dwindling and Disappearance of Limestones," *Quarterly Journa Geological Society*, Vol. XLIX (1893), p. 372.

But as carbonate deposits are characteristic of the open sea, so are silicious, feldspathic, and argillaceous deposits dominant upon the land surface, and thus a separate argument is derived for the view that in pre-Cambrian times the continents possessed at least their present extension, an argument, however, which requires further testing in regard to the premises as to the poverty of limestones.

It would seem, therefore, that the 12,000 feet of the Belt terrane, consisting, as it does, of from 37 to 50 per cent. of dolomitic limestones is far from being an occurrence holding an unusual proportion of continental deposits and that the conclusion derived from its study in regard to their presence in important quantity is therefore susceptible of wider application.

Reviews and Book Notices

Miocene Foraminifera from the Monterey Shale of California, with a Few Species from the Tejon Formation. By Rufus M. Bagg, Jr. (U. S. Geological Survey, Bulletin No. 268, 1905.) Pp. 55, 11 plates, 2 figures.

The Monterey Shale is 2,000–2,500 feet thick where the fossils were collected. This was near Asuncion, in San Luis Obispo County. The collecting was done by Professor Branner, of Leland Stanford University, who also wrote an introduction to the *Bulletin*.

The formation as a whole lies in a broad fold, but there are smaller folds and numerous faults. The bulk of the shale is made of diatom skeletons.

Dr. Bagg finds sixty-six species and seventeen genera in the collection. Most of them are common in the North Pacific today, so that conclusions may be drawn as to the temperature and depth of the water where these sediments were deposited. The water was probably less than 500 fathoms deep.

E. W. S.

The Lead, Zinc, and Fluorspar Deposits of Western Kentucky. By E. O. Ulrich and W. S. Tangier Smith. (U. S. Geological Survey, Professional Paper No. 36, 1905.) Pp. 218, 22 plates, 31 figures.

The geology and general relations of the deposits are discussed by Mr. Ulrich and constitute Part I of this paper; the ore deposits and mines are described by Mr. Smith in Part II. The region has been subjected to abundant faulting, and the surface is quite rough and irregular on that account. The deposits are somewhat similar to other deposits of similar ores in the interior of the United States, but there are a number of unique features in lithologic and mineralogic associations. One of these is the presence of basic igneous dikes. Another is the abundance of fluorspar, especially where the lead and zinc ores occur. Thirdly, the ores are found principally in true fissure veins, which have resulted from fracturing and subsequent faulting.

The minerals of economic importance are fluorite, barite, galena, sphalerite, and smithsonsite. In addition, there occur cerussite, pyromorphite, sulphur, hydrozincite, calamine, greenockite, chalcopyrite,

malachite, calcite, quartz, kaolinite, and ankerite. Fluorite is the main product of the mines, and lead and zinc might almost be regarded as by-products. Much of the ore must be cleaned before shipping, because the mines are working in the oxidized zone. The mining industry will grow more rapidly when a deeper zone is reached and the ore becomes cleaner, and when transportation facilities improve. E. W. S.

Climatic Features of the Pleistocene Ice Age. By PROFESSOR ALBRECHT PENCK. (Reprint from the *Geographical Journal*, February, 1906, pp. 182–87.)

Professor Penck, in this paper, approaches the problem of the climate of the Pleistocene Ice Age from the data of physio-geographical research. He thinks it likely that the pluvial periods, of which there is evidence in many of the deserts of the world, were contemporaneous with ice-advances, and that desiccation phenomena accompanied interglacial epochs. The world-wide parallelism of such events points to a common origin, which he thinks to be a very slight change of temperature. E. W. S.

The Transvaal Formation in Prieska, Cape Colony. By E. H. L. SCHWARZ. (Reprint from Transactions of the Geological Society of South Africa, Vol. VIII, 1905, pp. 88–103; 1 plate.)

This paper describes the parts of the Transvaal system and sums up what is known of it. A number of suggestions are made as to correlation with other formations in South Africa and formations in other countries. There is a very striking resemblance, both in lithological character and sequence, to the Huronian of the Lake Superior region. E. W. S.

Iron Ore Reserves. By CHARLES KENNETH LEITH. (Reprint from *Economic Geology*, Vol. I, No. 4, February-March, 1906, pp. 360–68.)

The exhaustion of the world's supply of iron ore has been put by many authorities at less than a century hence. Professor Leith holds that these estimates do not take the low grade ores sufficiently into account. Before the high-grade ores are exhausted the price of iron will have so advanced as to make profitable the working of immense bodies of ore which are not worked now. Accompanying this change will be widespread economic changes in matters related to the iron industry. E. W. S.